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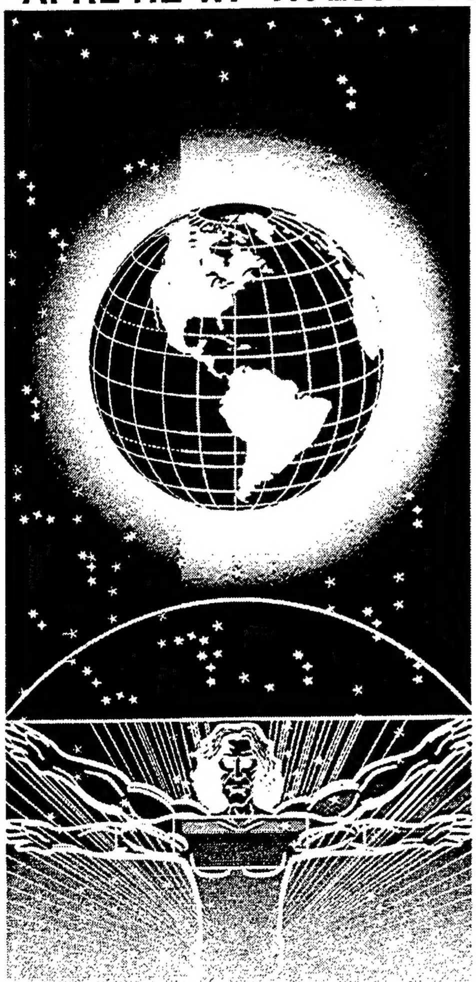

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MULTIMODAL DISPLAYS FOR TARGET LOCALIZATION IN A FLIGHT TEST

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FOR THE COMMANDER

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13. ABSTRACT ***(Maximum 200 Words)***

This study evaluated the role of adaptive cueing interfaces as a means of integrating visual and auditory displays for target designation and was conducted at the Air Force Research Laboratory's Synthesized Immersion Research Environment (SIRE) facility. Twelve pilots with a mean of 2652 flight hours performed a simulated flight task in which they were instructed to maintain a prescribed flight path, air speed, and altitude. Pilots visually searched out-the-window for ground and air targets. Seven target-location cueing conditions were employed which featured spatialized auditory, visual, non-adaptive multimodal, and adaptive multimodal display configurations. Designation accuracy was poorest in the non-cueing and spatialized auditory display conditions in comparison to the other display configurations. The addition of spatialized sound to visual cueing reduced target designation time in comparison to the visual cue alone in some conditions, and the time advantage form multimodal cueing was approximately 825 msec. Multimodal cueing also reduced head motion and lowered pilots' workload by approximately 30%. This study suggests that multimodal cueing may effectively aid target localization in tactical aviation and revealed no advantage or disadvantage for presenting multimodal information adaptively over presenting it in a fixed format; the benefits associated with multimodal information were identical in both fixed and adaptive formats.

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ABSTRACT

Tactical air missions place a high visual load on pilots, who must rapidly acquire and synthesize information from displays within the cockpit (near-domain) and events outside of the cockpit (far domain; Martin-Emerson & Wickens, 1997). The delivery of target-position information is especially critical, as even slight delays can have catastrophic consequences. The development of head-up (HUD) and helmet-mounted displays (HMD), which superimpose near-domain elements onto the far-domain scene and provide visual cueing to target position, has improved performance in target detection scenarios (Fadden, Ververs, & Wickens, 1998; Osgood, Wells, & Meador, 1995). While helpful, such technologies have restricted display areas, or fields-of-view (FOV; Davis, 1997), which limit their effectiveness in finding and designating targets. Recent research has shown that spatialized audio cueing can lead to increased detection rates, reductions in detection time, and reductions in workload during visual search tasks (Begault, 1993; Bronkhorst, Veltman, & Breda, 1996; Nelson, Hettinger, Cunningham, Brickman, Haas, & McKinley, 1998). However, research on spatialized auditory cueing when using HMDs has focused on opaque HMDs that present virtual environments as compared to the richer visual scene available via see-through HMDs typically found in operational settings. Therefore, one goal for the present study was to determine the benefits of combining auditory and visual cueing for target-designation performance during a simulated flight-task using a see-through, head-coupled visual display. It was expected that when compared to non-cued and unimodally cued conditions, multimodal audio-visual interfaces would lead to more efficient performance, particularly for targets initially outside of the display's field-of-view.

An important consideration for implementing displays is their interaction with existing interfaces. Cockpits have limited space for information display, and there is already a high visual demand that may contribute to information overload and increase the probability of pilot error (Reising, Liggett, & Munns, 1999; Weinstein & Wickens 1992). Combining visual cueing with auditory cueing might exacerbate that clutter. A promising approach to counteracting clutter is the use of adaptive interfaces, in which automation is employed to control the delivery of information

to pilots so that they receive the right information in the right format at the right time and are not otherwise exposed to that information (Hettinger, Cress, Brickman, & Haas, 1996; Hollnagel, 1988). This approach has been shown to be helpful to pilots during landing and navigational tasks (Brickman, Hettinger, Roe, Lu, Repperger, and Haas; 1996, Moroney, 1999). Accordingly, a second goal for the present investigation was to evaluate the role of adaptive cueing interfaces as a means of integrating visual and auditory displays for target designation. It was anticipated that performance with multimodal adaptive interfaces, which reduce cockpit clutter, would be superior to that associated with fixed-format multimodal interfaces.

The study was conducted at the Air Force Research Laboratory's Synthesized Immersion Research Environment (SIRE) at Wright-Patterson Air Force Base. Twelve experienced pilots (11 males and 1 female; mean 2652 flight hours) serving at the base participated in the study. While performing a simulated flight task in which they were instructed to maintain a prescribed flight path, airspeed, and altitude, pilots visually searched out-the-window for ground and air targets. The targets could initially appear either within or outside of the display FOV. Seven target-location cueing conditions were employed. They included a non-cueing control and six cueing interfaces. These head-coupled cueing interfaces featured auditory (headphone-delivered spatialized sound), visual (simulated HMD symbology), fixed multimodal (simultaneous auditory and visual), and adaptive multimodal display configurations. In the case of adaptive displays, the presentation of auditory and visual cues was determined by whether a target was positioned inside or outside of the HMD FOV. Thus, in the Adaptive Auditory plus Adaptive Visual condition, a target initially beyond the display FOV would be cued aurally. When the visual display encompassed the target in the display area, the auditory cueing would be replaced by the HMD-based visual cueing symbology. In the Adaptive Auditory plus Visual condition, auditory cueing was provided when a target was present outside the FOV, while visually cueing remained regardless of FOV. In the Adaptive Visual plus Auditory condition, visual cueing was only presented when the target was within the FOV, while auditory cueing was provided whenever a target was present. All pilots participated in all conditions. In addition to target designation accuracy and time, visual search performance was evaluated in terms of pilot head motion

because biomechanical fatigue is an important factor in the use of HMDs (Davis, 1997). Flight performance and NASA-TLX ratings were also collected to assess the impact of the several cueing interfaces on aircraft control and subjective workload.

Designation accuracy was poorest in the non-cueing and auditory display conditions in comparison to the visual, fixed multimodal, and adaptive multimodal conditions, which did not differ among themselves. Consequently, the non-cueing and auditory conditions were not considered in terms of designation time, and the visual cueing condition served as the principal baseline for that measure. The addition of spatialized sound to visual cueing reduced target designation time in comparison to the visual cue alone under conditions in which targets were most difficult to detect: ground targets initially outside of the field-of-view. Such targets had relatively low-contrast with the terrain, making it difficult to segregate them from the background, as evidenced by the lower hit rates for the ground as compared to the air targets. The time advantage for multimodal cueing (both fixed and adaptive) of approximately 825msec is of considerable practical significance, since even slight time advantages can be critical for tactical aviation (Barnes, 1989). The failure to find benefits for supplementary auditory cueing as compared to visual cueing alone in the other target type/FOV combinations may be attributable to the limited resolution of the auditory cueing system, as well as pilots' reliance on visual displays and their lack of experience with spatialized auditory cueing.

In addition to enhancing visual search performance, multimodal cueing had the added benefits of reducing excessive head motion and of lowering pilots' workload by approximately 30% in comparison to the case in which no cueing was available. Moreover, multimodal cueing did not interfere with the flight task; i.e. multimodal cueing did not incur a performance-resource debt (cf. Wickens, 1992). In sum, the present study suggests that multimodal cueing may effectively aid target localization in tactical aviation.

The present investigation revealed no advantage for presenting multimodal information adaptively over presenting it in a fixed format; the benefits associated with multimodal information were identical in both fixed and adaptive formats. The failure of the adaptive conditions to prevail over the fixed format conditions in this study may stem from the fact that the adaptive format was

not necessary in the flight scenario used here. Since the fixed multimodal interface did not interfere with the performance of the concomitant flight tasks, there was no added benefit in clutter reduction to be gained through the adaptive format. The usefulness of an adaptive format in reducing the demands of cockpit clutter when presenting multimodal information about target localization might emerge in a flight scenario in which the quantity and demand characteristics of near-domain information exceed those used in the present investigation.

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CHAPTER 1

Introduction

Summary of the Problem

One of the most challenging of human factors domains is tactical aviation. The complexity and dangers presented by such human-machine environments necessitate the development of display technologies that optimize pilot performance and minimize errors. Although recent developments in visual and auditory display technology have enhanced performance in flight tasks (e.g., navigation, target localization), there are unresolved issues concerning when and how to present critical information, especially given display limitations and the already information-loaded cockpit. The purpose of the present study was to evaluate the performance and demand characteristics associated with several visual and auditory display configurations (*interfaces*) designed to aid pilots in locating targets (cueing) during a simulated mission. The cueing configurations included single (unimodal) and combined (multimodal) auditory and visual displays, as well as adaptive display integration, in which the modality of presentation varied with situational demands.

The effectiveness of the interfaces was assessed via measures of target search and flight performance, as well as pilot head motion and perceived workload. It was expected that this research would provide guidance for the implementation of multimodal displays and for the utility of adaptive display integration, across a range of tasks, both within and beyond tactical aviation environments.

Information Load of the Tactical Cockpit

Information Acquisition. Tactical air missions impose high visual demands on pilots, particularly in single-seat fighter aircraft. In addition to the maintenance of proper course, altitude, and airspeed, pilots must perform several other functions, including weapons and fuel management, radio communication, and monitoring the environment for potential targets and threats. Successful performance of these tasks depends on pilots' ability to acquire and

synthesize information from different sources. These include *near-domain* information about system functions (presented by cockpit instrumentation) and *far-domain* (i.e., out-the-window) information about local airspace and terrain features (Martin-Emerson & Wickens, 1997). Pilots have attempted to develop efficient scanning methods to cope with these demands, but switching between domains is particularly challenging, because it requires rapid changes in line-of-sight (LOS) and optical focus, often under adverse physical (e.g., high-*g*) conditions. Such switching is also cognitively demanding, since pilots must pick-up and synthesize information across domains, thus creating a high potential for error (Weinstein & Wickens, 1992).

Visual Target Search. The need for rapid target acquisition is greatest in the context of threat engagements, where pilots must locate, identify, track, and designate potential air and ground targets, while flying complex attack maneuvers. Prior to the use of radar and other sensor-assisted target cueing, pilots relied on unaided sight in detecting and attacking the enemy. The development of radar provided assistance in finding targets (Koonce, 1999). However, it did not eliminate the need for visual search, and it added a new problem: In order to locate targets and also maintain system status, radar combined the continued need for out-the-window (OTW) scans (*head-up viewing*) with the need to look down at displays mounted below the aircraft windshield (*head-down viewing*). For example, during the dynamic attack phase of air-to-air combat, pilots must attend to far-domain events (visually acquiring and tracking target location) and near-domain data sources (e.g., monitoring radar; Barnes, 1989), an arrangement which, as indicated above, is far from ideal.

Visual Display Approaches to Improving Information Presentation

Head-Up Display (HUD). Given the value of air superiority and pilot survival, there is great impetus to improve information presentation in the tactical cockpit. One successful approach has been to design interfaces that combine the presentation of information from near and far domains and thus reduce the need to scan the domains separately. The primary technology to serve this function is the head-up display (HUD), a transparent display located between the pilot and the aircraft windshield upon which navigational and tactical information

(e.g., airspeed, altitude, target location) can be projected. HUDs are generally mounted at eye-height, and imagery is focused at optical infinity (Adam 1994). Looking through the HUD allows pilots to view the outside world and sample displayed information without changing their line-of-sight. Although originally developed to serve as aiming reticles or weapons sights, HUDs now provide pilots with additional information, such as navigational data and vectors to fly to targets (Reising, Liggett, & Munns, 1999). During target search tasks, a symbol portrayed on the HUD can indicate the position of a target in airspace (Geiselman & Osgood, 1995; Geiselman & Tsou, 1996), thereby eliminating the need to re-map information from a head-down display to the out-the-window scene (Barnes, 1989). A display such as this, which directly maps near-domain symbology onto far-domain external objects, is termed a *conformal* display.

The performance benefits of the HUD have been demonstrated in several different flight tasks in terms of decreased reaction time, error rate, and workload (Fadden, Ververs, & Wickens, 1998; Martin-Emerson & Wickens, 1997; Weintraub & Ensing, 1992). Moreover, tactical HUDs have become standard in most modern fighter/attack aircraft, including the United States Air Force's F-15, F-16, and F-117 (stealth fighter). However, they are by no means a panacea to problems of information acquisition. Like head-down displays, HUDs can present information to a pilot only when within his or her field-of-view (FOV). While a pilot's instantaneous FOV is approximately +/- 100^0 horizontal by +/- 60^0 vertical (Boff & Lincoln, 1988; Velger 1998), technical constraints have limited the HUD FOV to under 40^0 horizontal and vertical (Burley & LaRussa, 1990; Velger, 1998; Weintraub & Ensing, 1992), a relatively small portion of the total visible airspace. For example, lateral visibility in the F-15 extends approximately 150^0 in either direction (Burley & LaRussa, 1990). Accordingly, pilots are often unable to acquire near-domain information when looking out-the-window (OTW). Barnes (1989) has estimated that during the attack phase of threat engagements, pilots are looking out-the-window and away from the HUD about three quarters of the time.

A related constraint is the fixed *field-of-regard* (FOR) with respect to the far domain. Since the HUD is fixed to the aircraft's nose (*boresight*), its limited field-of-view can be modified only by moving the aircraft. This limitation is especially serious in air combat when the HUD is

used as a target designator and weapons sight. In these situations, it is impossible to designate off-boresight targets and it is often necessary to deviate from optimal attack maneuvers or flight paths in order to move the aircraft's boresight into appropriate position (Barnes, 1989; Velger, 1998). The development of high off-axis boresight weapon systems (HOBS) could allow for the designation of targets as great as 90^{0} off-nose (Beal & Sweetman, 1994; Velger, 1998). Taking advantage of HOBS weapons capabilities requires an interface that overcomes the HUD's limited field-of-regard.

Helmet-Mounted Display (HMD). The helmet-mounted display (HMD) can be considered the next significant development in tactical cockpit interfaces following the introduction of the head-up display. There are two general categories of HMDs (Melzer & Moffitt, 1997; Velger, 1998). Opaque HMDs, which present a virtual visual environment, are used primarily for simulation and training. See-through HMDs, derived from HUDs, allow conformal information to be portrayed on a transparent visor and are used in operational situations such as weapons targeting. Since a see-through HMD projects information on the helmet visor, displayed symbology is always within the field-of-regard. In order for HMDs to serve as effective target-cueing and designation systems, two additional components are added. A tracker measures head position in real time so that information is presented with respect to the pilot's line-of-sight, rather than a fixed position, such as the aircraft boresight. A helmet-mounted sight (HMS) allows pilots to use their head position as a control by coupling a reticle with the symbology on the HMD (Adam 1994; Velger, 1998). The integration of these components enables presentation of target location information, irrespective of field-of-regard. An example of HMD symbology is illustrated in Figure 1, in which a locator line referenced to the pilot's head position, indicates the direction to a target beyond the display field-of-view. Consequently, pilots can smoothly locate and track a target, and if appropriate, use the aiming reticle to designate a weapon off-boresight without re-positioning the aircraft (Barnes 1989; Geiselman & Tsou, 1996). Although first developed in the 1960s, airborne HMD designs were not implemented successfully until the 1980s, awaiting advances in both optical and weapon systems technologies (Melzer & Moffitt, 1997; Velger, 1998). A motivating factor for the development of these technologies in the U.S military has been

the implementation of helmet-mounted sighting systems by the South African, Russian, and Israeli air forces (Beal & Sweetman, 1994; McQuillan, 1999).

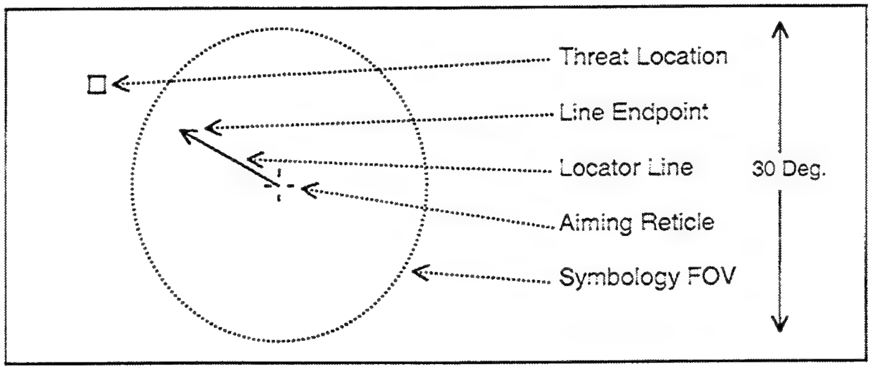


Figure 1. HMD target localization and designation symbology (adapted from Geiselman & Tsou, 1996).

For tactical situations, HMD systems have a number of advantages over head-up displays. Figure 2 illustrates the field-of-regard limitations for HUDs relative to HMDs with respect to the directional range of sensor systems including radar and infrared (FLIR). Note that the HUD has a relatively narrow field-of-regard that does not cover the entire directional range of sensors. In comparison, the HMD, which accounts for head movement, enables information display that exceeds the total directional range for sensors (Merryman, 1994; Velger, 1998).

Although much of the research on operational HMD efficacy remains classified (E.E. Geiselman, Air Force Research Laboratory, personal communication, March 15, 1999), several studies are available in the literature which indicate performance benefits for HMDs. Arbak, King, Jauer, and Adam (1988) found that pilots flying simulated air-to-air combat missions achieved a greater number of kills and a greater *exchange rate* (ratio of kills to losses) when using HMDs in conjunction with HUDs than when using tactical HUDs alone. Moreover, the pilots reported a number of advantages to HMD use, including reduced time-to-shoot by steering their heads instead of the aircraft. In a similar study, Olson, Arbak, and Jauer (1991) reported a 21% increase in exchange rate when HMDs supplemented the HUD.

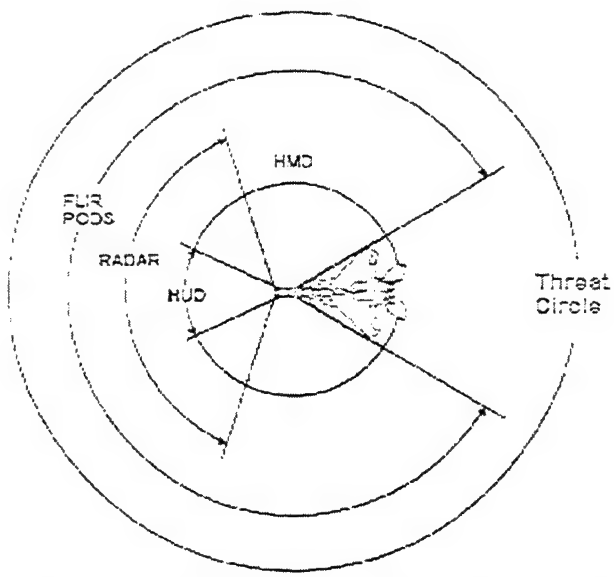


Figure 2. Field-of-regard ranges for HUD, sensors, HMD, and potential threats (adapted from Velger, 1998).

HMDs have also been shown more effective than HUDs in air-to-ground combat scenarios. Since ground targets can be masked by the terrain, they are typically more difficult to locate. Osgood, Wells, and Meador (1995) compared performance with and without HMD-based target cueing during simulated low-altitude ground attack missions. Compared with the HUD alone, use of the HMD resulted in releasing weapons more rapidly and at a greater distance from targets. Pilots were also able to designate targets farther off boresight, thereby taking fuller advantage of HOBS weapons capabilities. Again, the participating pilots reported HMD speed advantages for target designation.

Helmet-mounted displays improve the linkages between pilot, sensor, and weapons systems. Freeing the pilot from a fixed boresight field-of-regard improves both target acquisition and kill rate. However, HMDs are limited in their utility. Like HUDs, helmet-mounted displays have obstacles that limit the area onto which information may be projected. For a *fixed* field-of-regard (i.e., with the head stable), see-through HMDs have approximately the same display field as HUDs (Davis, 1997; Wells & Haas, 1990). This constraint is partly determined by current HMD designs that require that the helmet-mounted projection system be supported by the pilot's head and neck, resulting in a tradeoff between display FOV and helmet size and weight. Increasing the

display area would require an increase in helmet size, which is constrained by the *ejection envelope* (cockpit-space requirements for safe pilot ejection). Additionally, increasing helmet size/weight could reduce scanning performance and endurance and increase the probability and severity of head/neck injury (Dudfield, Hardiman, & Selcon, 1995; Perry & Buhrman, 1997; Wells & Venturino, 1990). Moreover, while a limited display area allows for relatively unobstructed sight in see-through HMDs, it necessitates head movements for repositioning symbology (*sluing),* which are less efficient than saccadic eye movements (Davis, 1997). However, Davis (1997) has pointed out that extreme eye movements required by larger FOV displays would be uncomfortable, and recommends limiting them to +/- 15^0 of the central line-of-sight. The optimal tradeoff between display area, weight, and performance remains to be determined. Given this uncertainty, it seems worthwhile to determine whether HMD efficacy can be enhanced by providing information via other sensory modalities.

Auditory Cueing

Spatialized Sound. Since the perception of a sound source is limited neither by field-of-regard nor line-of-sight, several researchers have proposed that auditory cueing be used to improve visual target search performance (McKinley, Ericson, & D'Angelo, 1994; Perrott, Cisneros, McKinley, & D'Angelo, 1996; Rudmann & Strybel, 1999). Perrott, Saberi, Brown, and Strybel (1990) suggested that vision and audition can function synergistically in search tasks by enabling auditory localization to direct the visual system toward objects in space. They found that presentation of a spatially coincident *free-field* sound (originating from an actual source) with a visually presented target resulted in significantly reduced search times. Gains in search efficiency were greatest when targets were presented outside participants' fields-of-view. However, auditory cueing still reduced search times within the central 10^0 of the FOV by an average of 175msec. The authors suggested that aurally conveyed information is used to initiate and modify appropriate head movements.

Perrott, Sadralodabai, Saberi, and Strybel (1991) more closely explored the effectiveness of auditory cueing in the central FOV (< 15^0). The effectiveness of the sound cue was again a

positive function of angular distance from line-of-sight. There was a significant benefit in search times for the most distal targets of about 100msec, but no benefit for targets within the central line-of-sight (< 3^0). These studies show that the benefits of auditory cueing in visual search tasks are maximal when targets are beyond an observer's central field-of-view.

Rudmann and Strybel (1999) proposed that the utility of auditory cueing lies in its conveying general rather than precise information about target location. To explore this possibility, they utilized a method developed by Williams (1973) to analyze visual search performance in two phases, localization and identification. Localization occurs in the first stage of the search process, where a target is brought into the field-of-view. The precise target position within the field-of-view is determined during the succeeding identification stage. Rudmann and Strybel found that sound helped in both stages of the task, with the greater benefit of auditory cueing accruing to target localization.

Virtual Auditory Displays. Implementing spatialized sound in cockpits requires the use of synthetic audio generators to spatially render target positions and deliver them to binaural cockpit headsets as positional audio cues. The use of digital filtering systems allows for the rendering of sound sources at any positions in space (Shinn-Cunningham, Lehnert, Kramer, Wenzel, & Durlach, 1997; Wenzel, Arruda, Kistler, & Wightman, 1993). These filters are based on the measurement of head-related transfer functions (HRTF): that is, intensity and phase transformations of sound resulting from reflection/ attenuation by the listener's body, head, and pinnae (Wightman & Kistler, 1989 a, b). The transfer functions may be individualized (derived from measurements from an individual) or generic (derived from a representative model). In general, since only a limited number of positional sound samples are taken to compute HRTFs, mathematical interpolation is required to render sounds between sampled positions, contributing to a drop in resolution. As with HMD symbology, spatialized auditory displays can be coupled with head-tracking systems to allow information to be presented with respect to changing head position and orientation.

Although virtual audio displays do not provide the same resolution as free-field sound sources, they can nevertheless improve performance in localization tasks (Bolia, D'Angelo, &

Mckinley, in press; Perrott, Cisneros, McKinley, & D'Angelo, 1996). Begault (1993) evaluated the utility of three-dimensional auditory cueing[1] (using generic HRTFs) in locating moving visual targets. Flight crews flew a simulated collision-avoidance mission in which they were required to search out-the-window for air traffic. Pilots using localized sound acquired aircraft over two seconds more quickly than with non-localized auditory warnings. Similarly, Bronkhorst, Veltman, and Breda (1996) found that when presented in a flight simulator, virtual auditory cues were of significant value in helping pilots locate and track target aircraft, especially when they were presented in combination with visual displays.

Another context in which auditory cueing has proven effective is in the acquisition of targets located within highly distracting environments (Perrott, Sadralodabai, Saberi, & Strybel, 1991). Distracters can consist of a variety of stimuli ranging from elements designed to look like targets, to the background in which targets are embedded, such as camouflaging terrain. Bolia, D'Angelo, & McKinley (in press) evaluated reaction times for target detection in varying *distracter ratio* environments (ratio of number of distracters to a target), under non-cueing, free-field, and virtual audio conditions. The authors demonstrated that virtual auditory cueing not only enhanced acquisition speed to near that of free-field sound, but also significantly minimized the negative effect of high-distracter ratios. Accordingly, virtual audio may be particularly useful in assisting the localization of targets under non-optimal visual conditions, such as ground target detection.

Adding sound to the HMD system is a natural extension of designing displays in terms of a perceptual system rather than independent senses (cf. Gibson, 1966). Melzer and Moffitt (1997) point out that head-down displays essentially nominate vision as the effective perceptual system, without accounting for head-motion nor the other sense modalities. Helmet-mounted displays can be referenced to head-position, thereby leveraging the functionality of vision. Accordingly, it makes sense to include audition, which can influence head and eye movements (Perrott et al., 1991; Rudmann & Strybel, 1999), as a part of the interface design. This is especially relevant for helmet-mounted sights because head position, in conjunction with aircraft

[1] Begault utilized exaggerated audio cues to accentuate localization direction in the horizontal plane by mapping sound sources to three times the angular distance as the corresponding visual position. For example, a target that was 15 degrees off axis would sound as if it were 45 degrees off.

position, controls target designation systems.

Recent research has addressed the use of virtual spatialized audio in conjunction with limited field-of-view HMDs for visual target search. This work employed opaque rather than see-through HMDs to present a low-fidelity, virtual visual environment in which participants could search for targets without conformal symbology. Since such HMDs have highly constrained visual fields, they lend themselves readily to the inclusion of other modalities (Davis, 1997). In the absence of supplementary visual cueing (e.g., locator lines - see Figure 1), the presence of virtual auditory cueing led to increased detection rates and decreased detection times, and to reductions in reported workload (Cunningham, Nelson, Hettinger, Russell, & Haas, 1995; Nelson, Hettinger, Cunningham, Brickman, Haas, & McKinley, 1998). In addition to these performance and workload benefits, virtual auditory cueing also improved the efficiency of search patterns, as revealed through analyses of participants' head motion (Cunningham, et al. 1995; Nelson, et al. 1998).

While the results of research combining virtual auditory with HMD technology are impressive and theoretically sound, it is important to emphasize that they did not provide supplementary visual cueing. See-through HMDs, which provide conformal symbology, are more common in operational settings, and it is not clear whether the beneficial effects of added auditory cueing would also accrue to these types of HMDs. More specifically, users can rely on the conformal symbology of see-through HMDs (along with rich views of the outside world) to locate targets. Additionally, Flanagan, McAnally, Martin, Meehan, and Oldfield (1998) have demonstrated that when visual target cueing is available in an opaque HMD, auditory cueing may be of no additional benefit in aiding a visual search task. Accordingly, one goal for the present study was to assess the effects on performance and perceived workload of virtual auditory cueing on target acquisition with a *see-through* visual display and sight.

Interface Management

Cockpit Clutter. Helmet-mounted displays and virtual auditory cueing offer performance and workload advantages to pilots; however, integrating these technologies into the cockpit is not a simple matter. It requires consideration of their interactions with existing interfaces and with

one another. Single-seat aircraft cockpits, such as that in the Air Force's premier lightweight fighter, the F-16C Falcon, have relatively limited space for information display. Moreover, there is already a high display load in cockpits, and too many displays may contribute to information overload, increasing the probability of pilot error (Reising, Liggett, & Munns, 1999; Weinstein & Wickens 1992). The unlimited field-of regard of HMDs, and the omnidirectonal character of auditory displays might exacerbate that clutter.

Adaptive Interfaces. An emerging approach to counteracting clutter is the use of adaptive interfaces, in which automation is employed to control the delivery of information to pilots so that they receive the right information in the right format at the right time, and are not otherwise exposed to that information (Hettinger, Cress, Brickman, & Haas, 1996; Hollnagel, 1988). The utility of such a situation-dependent display is illustrated in a study by Brickman, Hettinger, Roe, Lu, Repperger, and Haas (1996), who used an adaptive force-reflecting aircraft control stick to aid in landings during calm and turbulent flight conditions. The control stick operated normally when the aircraft was correctly aligned with the runway. However, whenever the aircraft deviated laterally from a pre-determined flight path, the stick provided increased resistance against control inputs that would further increase the deviation. The control stick offered no benefit over a standard stick under calm flight conditions, but under turbulent conditions aircraft landings were more accurate with the haptically-augmented control stick than with its standard counterpart. In addition to landing functions, other studies have shown that providing necessary information only during critical situations can also be of effective value to pilots during navigational tasks (Bennett, Cress, Hettinger, Stautberg, & Haas, in press; Moroney, 1999). Accordingly, a second goal for the present investigation was to evaluate the role of adaptive interfaces as a means of integrating visual and auditory displays for target designation. In brief, it was expected that when compared to unimodal and non-cued conditions, multimodal audio-visual interfaces would lead to higher target detection rates and faster search times, particularly for targets that were initially outside of the display symbology field- of-view. It was also anticipated that performance with multimodal adaptive interfaces, which reduce cockpit clutter, would be superior to that associated with fixed-format multimodal interfaces.

CHAPTER 2

Method{tc \l1 "METHODS }

Participants{tc \l2 "Participants}

Twelve pilots (11 males and 1 female) serving at Wright-Patterson Air Force Base participated in the study. They ranged in age from 32 to 51 years, with a mean of 40 years. All had normal or corrected-to-normal vision, based upon Snellen acuity, and normal auditory functioning: threshold at 500Hz to 4000Hz: 25dB SPL or better (ANSI, 1969). Each pilot had at least 1500 hours of flight experience in military aircraft, such as training (T-37; T-38), fighter (F-4; F-15; F-16), and transport (C-130; KC-135) jets, with a mean of 2652 hours logged.

Experimental Design{tc \l3 "Experimental Design}

As shown in Table 1, seven target-cueing conditions were employed in this experiment. They included a non-cueing control and six cueing interfaces. The cueing interfaces featured unimodal auditory, unimodal visual, and multimodal (auditory and visual) displays presented in fixed or adaptive configurations. All pilots participated in all conditions.

Table 1
Cueing Conditions.

Target Cueing Interfaces
Non-Cueing [Non]{tc \l3 "Non-Cueing}
Fixed Format: Auditory [Aud]
Fixed Format: Visual [Vis]
Fixed Format: Auditory plus Visual [A+V]
Adaptive Format: Adaptive Auditory plus Adaptive Visual [Adap(A+V)]
Adaptive Format: Adaptive Auditory plus Visual [Adap(A)+V]
Adaptive Format: Adaptive Visual plus Auditory [Adap(V)+A]

Apparatus and Procedures{tc \l3 "Apparatus and Procedures}

Laboratory Facilities. The study was conducted at the Air Force Research Laboratory's Synthesized Immersion Research Environment (SIRE) at Wright-Patterson Air Force Base. As illustrated in Figure 3, the SIRE facility houses a simulated F-16C cockpit situated in the center of a 20′ radius dome that includes a high-resolution, large field-of-view (70^0 vertical by 150^0 horizontal) interactive visual display. For experimental testing, the cockpit was raised 7.5′ to place pilots' eyeheight at the approximate vertical midpoint of the dome. The fixed-base cockpit contained head-up and head-down visual displays and F-16 throttle and sidestick aircraft controls. Out-the window (OTW) imagery consisted of desert-like terrain with rolling hills (southwest New Mexico, see Figures 4a,b). It was generated by a Silicon Graphics Onyx Reality Engine 2 computer and presented by a set of six Barco cathode ray tube projectors, each providing 1280 horizontal x 1024 vertical pixel resolution. The beams from the six projectors were calibrated to provide a single, coherent image on the dome display. The Reality Engine also generated air and ground targets, as well as the visual target cueing and designation symbology. All additional visual (cockpit displays) and auditory (target cueing and performance feedback) stimuli were generated by Intel processor-driven personal computers, which controlled trial sequences and collected data.

Flight Task. Pilots were instructed to maintain an airspeed of 500 knots while flying at or below 300′ *AGL* (above ground level). The flight task also required pilots to minimize lateral deviation from a waypoint-guided path. There were three waypoints, or turning points, during a flight, which were spaced approximately 19.5 miles apart (see Figure 5). Pilots determined deviation from the flight path through a Horizontal-Situation-Display (HSD), which was located in the left side of the cockpit. As illustrated in Figure 6, this head-down display portrayed a top-down view with the pilot's aircraft at the center. The circles indicated waypoints and the lines connecting the waypoints depicted the flight path. Additionally, a head-up display (HUD), having a 30^0 field visual field, provided avionics information, including aircraft heading, airspeed, and AGL altitude, as shown in Figure 7.

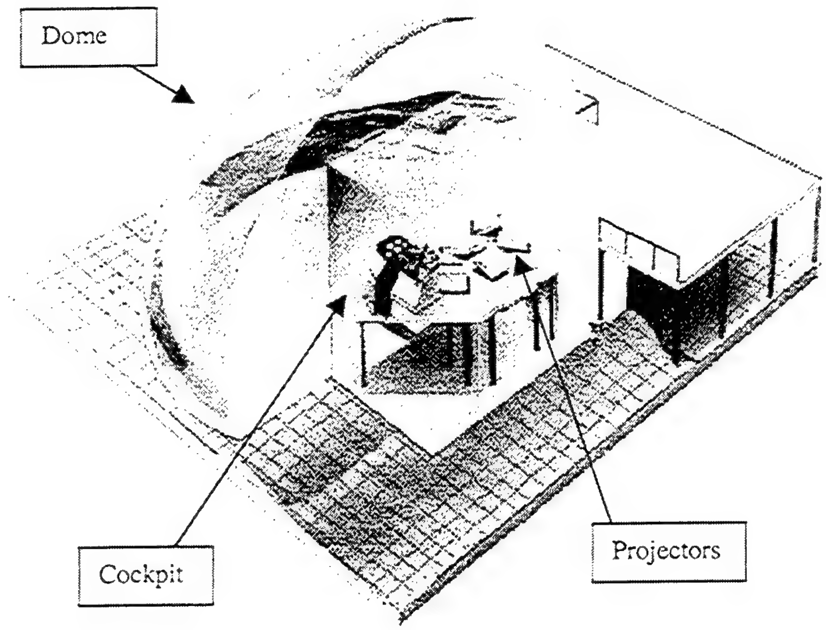


Figure 3. SIRE facility including cockpit-station, dome, and projectors.

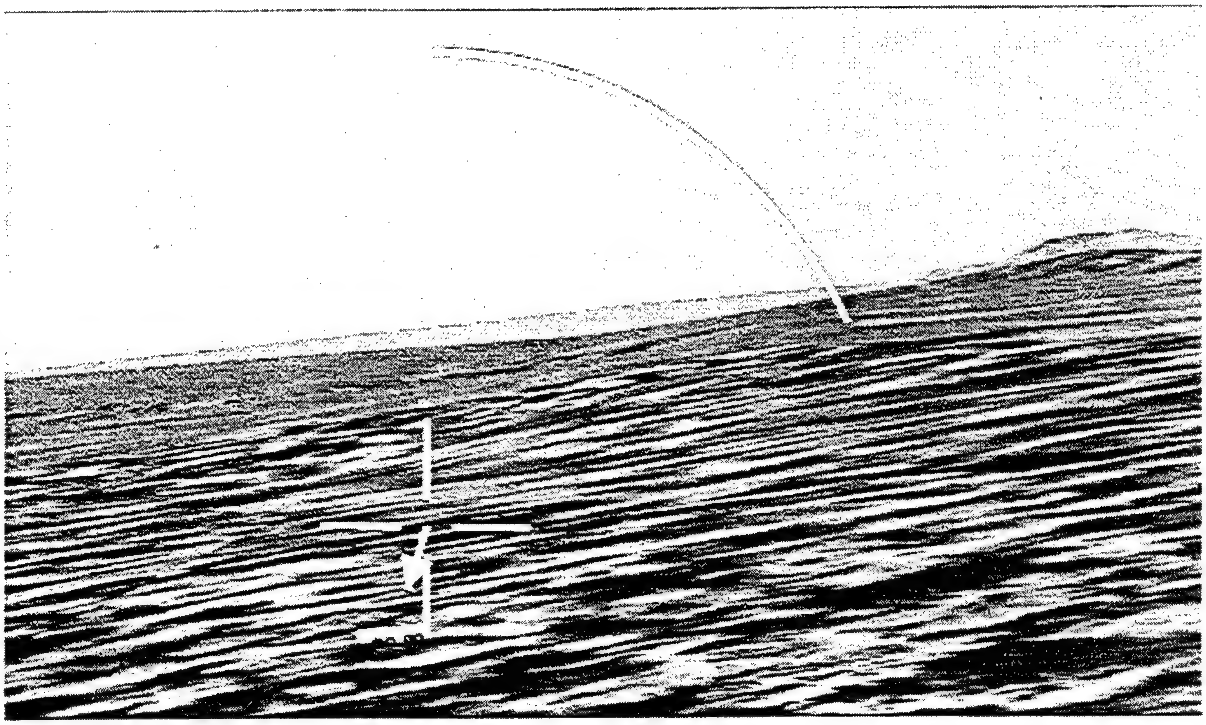


Figure 4a. Detail of dome-projected out-the window graphics and HMD symbology. This image, which is approximately 30 x 30 degrees visual angle, shows a ground target approximately 3000' away at terrain level.

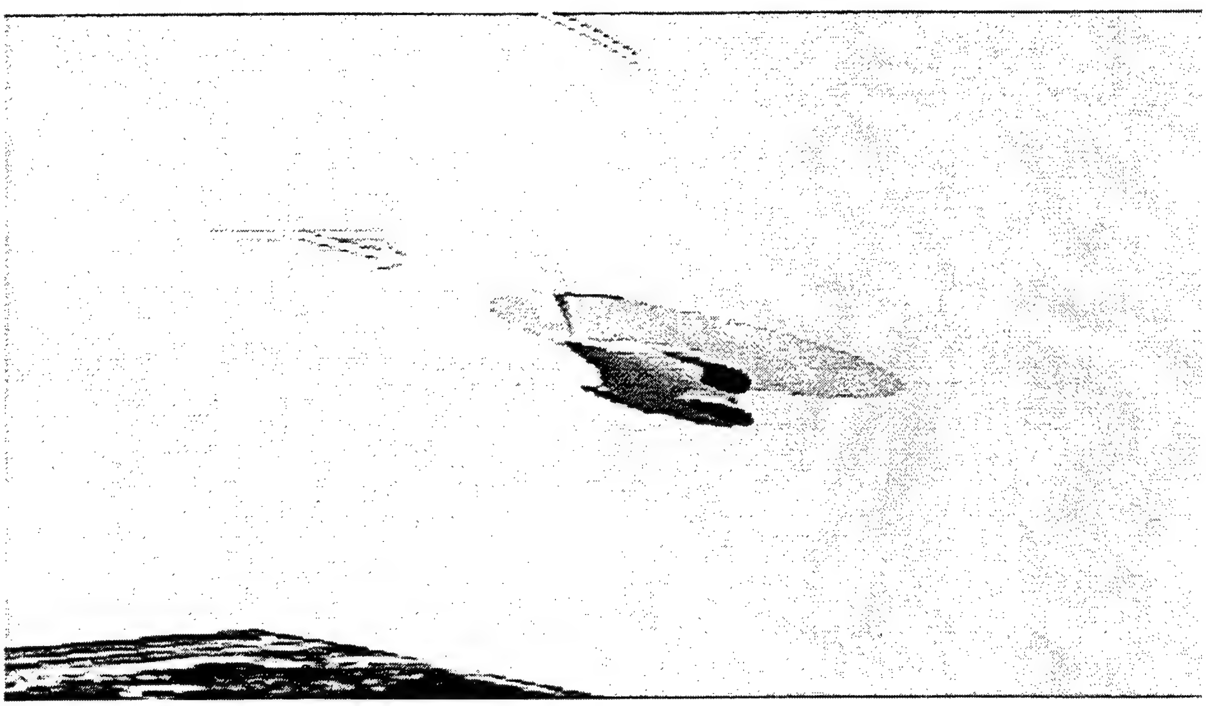


Figure 4b. Detail of dome-projected out-the window graphics and HMD symbology. This image, which is approximately 30 x 30 degrees visual angle, shows an air target approximately 500' away and 300' above the terrain.

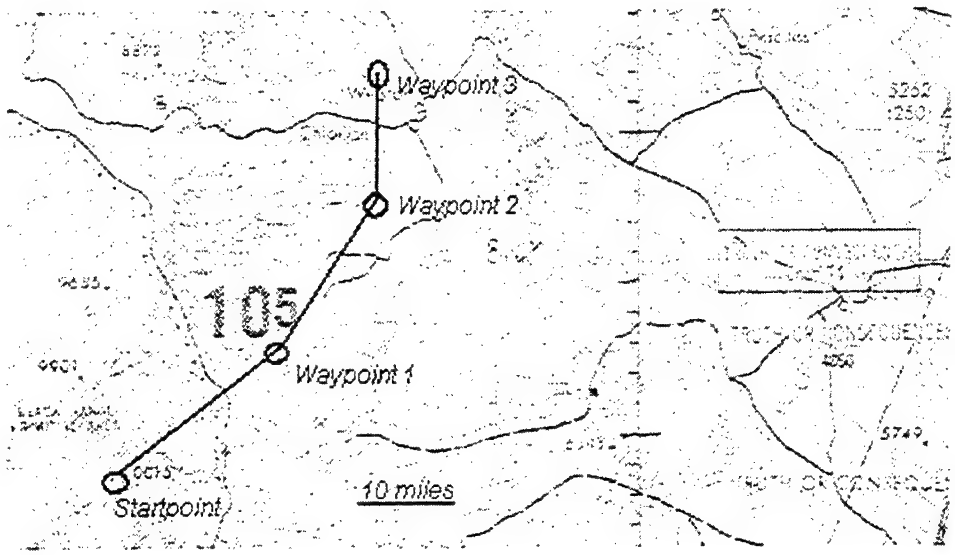


Figure 5. Typical flight path superimposed over section of New Mexico terrain map. Starting position and navigational waypoints are indicated.

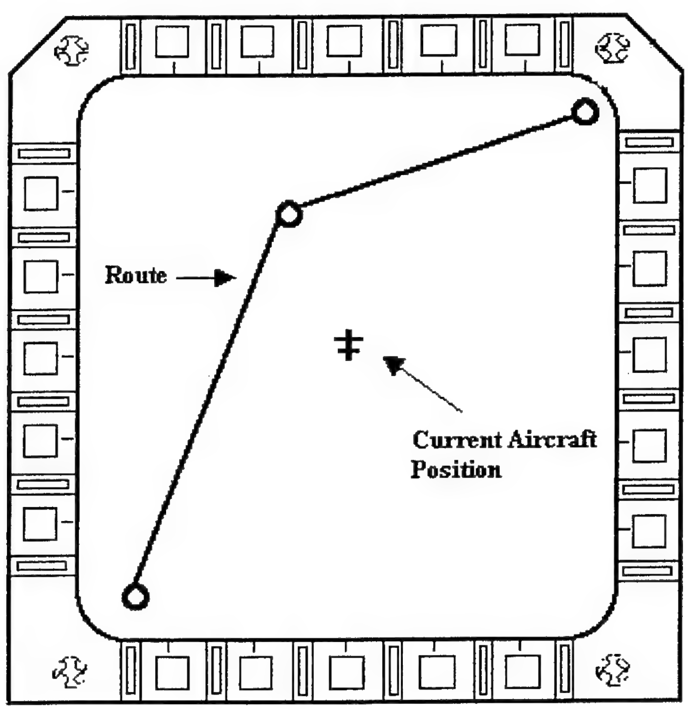


Figure 6. The horizontal situation display (HSD) presented an aircraft-centric view of the flight path and waypoints, allowing a pilot to determine and correct lateral deviation from the path.

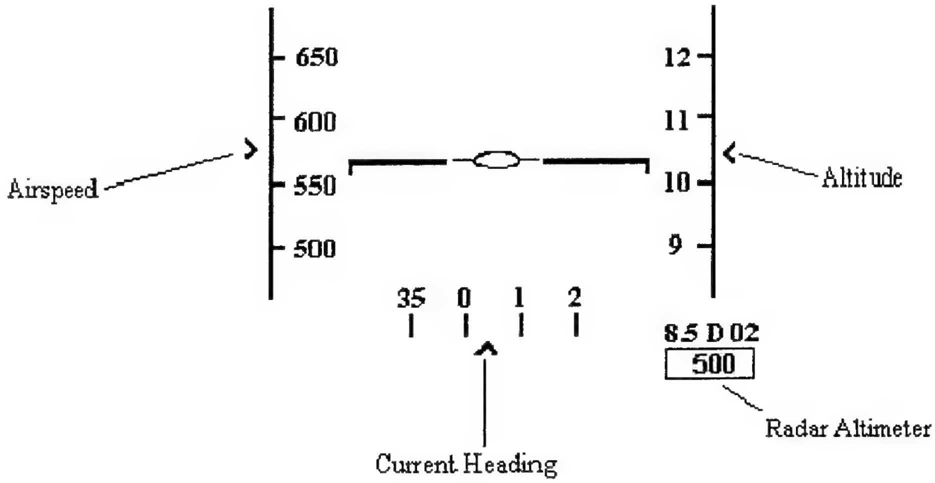


Figure 7. The head-up display (HUD) provided airspeed, above-ground-level altitude, and course deviation information.

Target Designation Task. While maintaining the directed flight path, airspeed, and AGL altitude, pilots visually searched out-the-window for ground (SCUD launcher vehicles, Figure 4a) and air (MH-53 helicopters, Figure 4b) targets. Each trial contained eight ground and eight air targets which were distributed randomly along the flight path, with the following four constraints. (1)Targets ranged laterally between 2000′ and 4000′ from the flight path; (2) each target was a minimum of 15000′ from subsequent targets, so that pilots would only have to locate one at a time; (3) ground targets were positioned at ground level, air targets at 300′ AGL; (4) targets did not appear until they were within 12000′ of the pilot's aircraft.

Pilots were instructed to visually locate and designate targets as *quickly as possible.* Designation was accomplished by moving a head-coupled aiming reticle (cross hairs; Figures 4a,b) over a target and depressing the appropriate control-stick button: weapons release for ground targets, trigger for air targets. The reticle was projected on the dome outside the cockpit, but was coupled with pilot head position, so that it simulated a helmet-mounted sight. Head position was measured by an Ascension Technology Flock of Birds electro-magnetic tracker, with the receiver mounted on a flight helmet. The helmet also housed a set of Sennheiser HD 250 II

binaural headphones for the delivery of auditory stimuli. A correct designation (hit) required pilots to depress the proper control-stick button while the cursor was within 3^0 of the target. Feedback for hits consisted of a 1.25sec change in cursor color (green to red), paired with a simultaneous 1000hz non-spatialized tone, presented at an intensity of 70dBA. Targets could not be designated more than once.

Target Location Cueing Interfaces. Under all but the Non-Cueing condition, visual and/or auditory cues were provided to aid in locating targets. In situations where visual cueing was provided, the reticle was augmented by target location and range symbology which, like the reticle, was projected on the dome and slaved to the pilots' head position to *simulate* a see-through HMD. Target location was displayed by an arrow that originated from the center of the reticle. As shown in Figures 4a,b, the length of the arrow represented the *angular distance* (distance in degrees from head position) to the target. It was scaled so that its linear extent would not exceed 15^0 visual angle. The direction of the arrow indicated to pilots which way to look. Range to target was portrayed by a circle (30^0 diameter) surrounding the reticle. A full circle would be displayed at the onset of cueing (range = 12000′). The *displayed circumference* of the circle would decrease with decreasing target range (e.g., a half circle at 6000′, a quarter circle at 3000′).

Where auditory cueing was provided, white noise pulses (250msec at 70dBA) were employed to portray target range and position. Target range was indicated by inter-pulse intervals, which decreased from a maximum of 1000msec at 12000′, to a minimum of 560msec at 1600′. Target position was indicated by digitally spatializing the sound in azimuth and elevation with respect to the instantaneous head position by means of a Convolvotron audio rendering system. Spatialization was based on generic head related transfer functions (HRTF)[2].

In the case of the fixed displays (Auditory [AUD], Visual [VIS], and Auditory plus Visual [A+V]), auditory and/or visual cues appeared whenever a target was present. In the case of adaptive displays, interface switching was determined by the presence of the target within the

[2] Localization transformations were performed by interpolating position based on a data set containing 72 fixed-distance filter pairs (left and right ears). These pairs were sampled at 15-degree increments from six elevations on a sphere.

helmet-mounted display's field-of-view (FOV). As suggested by Davis (1997), FOV was set at a 30^0 degree circular aperture, thereby limiting excessive eye movement and reflecting the limited viewing area of many helmet-mounted-display (HMD) systems (Adam, 1994; Melzer, 1998; Wells & Venturino, 1990). Thus, in the Adaptive Auditory plus Adaptive Visual [Adap(A+V)]condition, a target initially beyond the display FOV (+/- 15^0 in any direction) would be cued aurally. When the pilot moved his or her head to encompass the target in the display area, the auditory cueing was replaced by the HMD-based visual cueing symbology. In the Adaptive Auditory plus Visual [Adap(A)+V] condition, auditory cueing was provided while a target was present outside the FOV, while visually cueing remained regardless of FOV. In the Adaptive Visual plus Auditory [Adap(V)+A] condition, visual cueing was only presented when the target was within the FOV, while auditory cueing was provided whenever a target was present. In all conditions that provided localization cues, auditory and/or visual cueing disappeared whenever a correct designation was made, or if the target was bypassed.

Experimental protocol. For each cueing or interface condition, pilots completed a block of five consecutive trials in which they flew from waypoint to waypoint, searching for targets while maintaining the appropriate flight parameters. Crashing into terrain or flying above 2000' resulted in a failed trial, which was re-run at the end of the trial block. Each block lasted approximately 330sec. Immediately following the completion of each experimental condition, pilots assessed the perceived mental workload of the task (the information-processing load imposed by the task, Eggemeier, 1988; O'Donnell & Eggemeier, 1986) via the NASA-Task Load Index (TLX), a widely used instrument for measuring subjective workload, which provides a reliable index of overall workload (test-retest correlation =. 83) on a scale of 0 to 100 (Hart & Staveland, 1988; Hill, Iavecchia, Byers, Zaklad, & Christ, 1992; Nygren, 1991; Procter & Van Zandt, 1994).

Pilots were afforded a 5-minute break between cueing conditions. The order in which they experienced the several interface conditions as they progressed through the experiment was determined at random for each individual. The first two conditions to be experienced were tested on the first day of a pilot's participation in the study, with the remaining conditions tested on a subsequent day. The two testing sessions were separated by no more than two days. In all

experimental conditions, data regarding search performance were collected in terms of target designation accuracy and time (the time needed to correctly designate a target after it appeared). In addition, data on flight performance (deviation from flight parameters) and head motion were recorded five times/sec during each trial. All data collection was managed by computer.

Training. Prior to reporting for the experiment, pilots reviewed detailed written descriptions of the flight tasks and cueing interfaces. They received approximately two hours of verbal and hands-on training on the first day of participation. Under each experimental condition, training trials were run until the flight path was flown to its completion with a minimum of 25% of the targets properly designated. All pilots completed the training phase successfully. On the first day of participation, pilots were given a 10-minute rest between the end of training and the beginning of testing.

CHAPTER 3

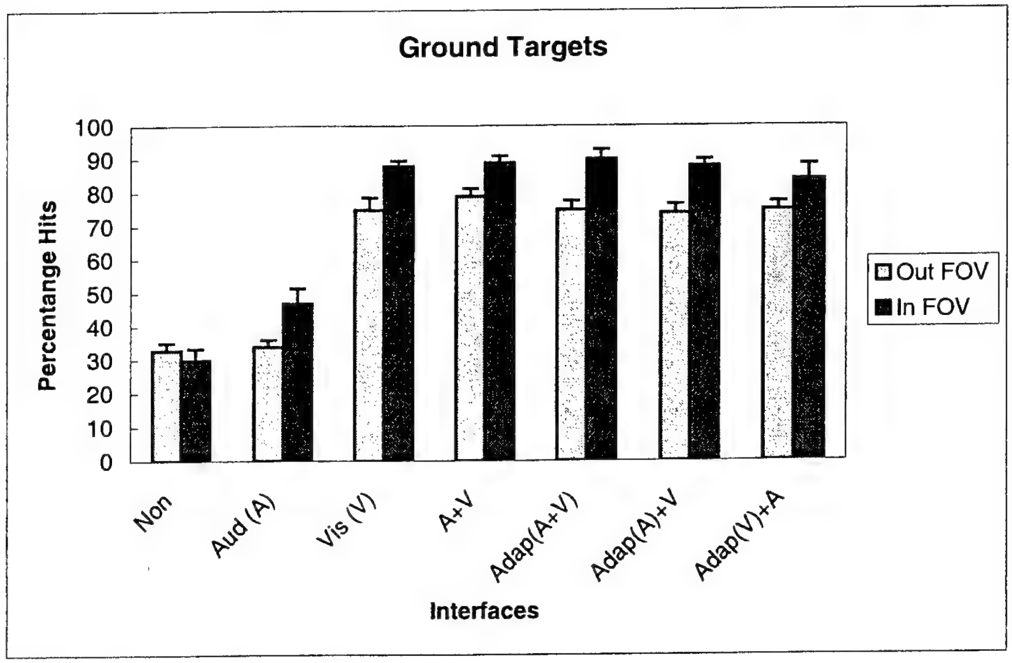
Results

Visual Search Performance

Target Designation Accuracy. The percentage of correct target designations (hits) across the five trial blocks was determined for each participant for each cueing condition. Mean percentages of hits for targets that were initially outside (+/-15^0 from the reticle) and initially inside of the display field-of-view (FOV) are plotted for the seven interface conditions in Figure 8. Data for ground and air targets are presented in the upper and lower panels, respectively. It can be seen in the figure that with the exception of the Non-Cueing [Non] ground target condition, the hit rate was greater for targets initially within the FOV (M= 83%) than for those initially outside of the FOV (M = 75%) and that in both FOV locations, scores for the Non-Cueing [Non] and the Auditory [Aud] conditions were consistently lower than those for the other conditions. It can also be seen in the figure that the overall frequency of correct target designations was greater for air (M = 89%) than for ground (M = 69%) targets.

The data of Figure 8 were converted to arcsines (Winer, Brown, & Michels, 1991) and tested for statistical significance by means of a 2 (target) x 2 (FOV) x 7 (interface condition) completely repeated measures analysis of variance (ANOVA)[3] In this and all subsequent ANOVAs, Box's epsilon was used in computing degrees of freedom to correct for violations of the sphericity assumption as determined by Mauchly's test (Maxwell & Delaney, 1990). Significant main effects were found for target type, $F(1,11) = 463.6$, $p < .05$, $\omega^2 = .26$, FOV, $F(1, 11) = 99.89$, $p < .05$, $\omega^2 = .08$, and interface condition, $F(3, 40) = 61.64$, $p < .05$, $\omega^2 = .37$, and there was a significant target type x interface interaction , $F(3, 40) = 17.20$, $p < .05$, $\omega^2 = .05$. All of the remaining sources of variance in the analysis were not significant, $p > .05$ in each case.

[3] Complete summaries of the results for this and the other analyses of variance in this study can be found in Appendix A.



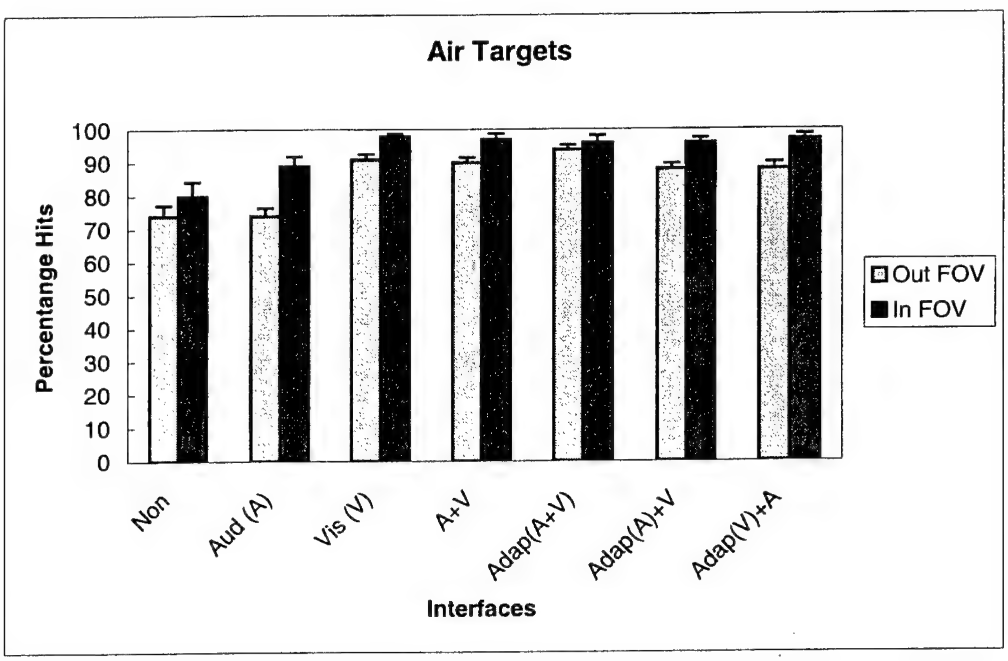


Figure 8. Mean percentages of ground (upper panel) and air (lower panel) target designations for the seven interface conditions. Data are provided for targets initially outside and inside the central field-of-view (FOV). Error bars are standard errors.

The Target x Interface interaction is displayed in Figure 9. Mean percentages of correct air and ground target designations are shown for the seven interface conditions. For each type of target, separate ANOVAs revealed that there were statistically significant differences among the interfaces, $\underline{F}_{ground}(3, 40) = 77.50$, $\underline{p} < .05$, $\omega^2 = .84$; $\underline{F}_{air}(3, 40) = 18.00$, $\underline{p} < .05$, $\omega^2 = .57$. Supplementary Newman-Keuls tests (alpha = .05 for each comparison) indicated that the hit rate for ground targets in the Auditory [Aud] condition was significantly greater than that for the Non-Cueing [Non] condition, and the means for each of these conditions were significantly lower than those for each of the five remaining interface conditions. The scores for these latter conditions, however, did not differ significantly from each other. With regard to air targets, the Newman-Keuls tests yielded an identical outcome, with the exception that the Non-Cueing and Auditory conditions did not differ significantly from each other.

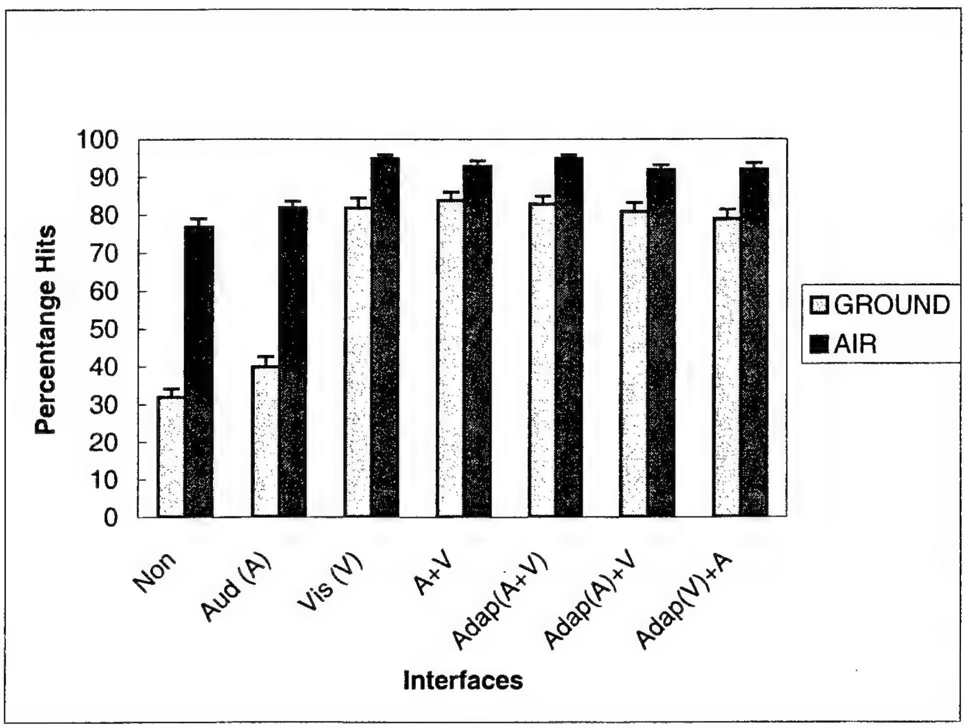


Figure 9. Mean percentages of ground and air target designations (collapsed over field-of-view) for the seven interface conditions. Error bars are standard errors.

Designation Time. Designation time scores for each participant were determined by averaging across trial blocks within each cueing condition. Mean designation times for targets

initially outside and initially inside of the FOV are plotted for the Visual cueing and the four auditory and visual cueing conditions in Figure 10. Data for ground and air targets are presented in the upper and lower panels, respectively. Scores for the Non-Cueing and the Auditory cueing conditions were excluded from this analysis because their relatively low hit rates would severely restrict the number cases in which correct designation times were based, and thereby lower the reliability of the those values. The most conspicuous feature of the data of Figure 10 is the considerable difference in the time of designation for ground (M = 5089msec) in comparison to air targets (M = 3696msec).

The designation time scores were tested for statistical significance by means of a 2 (target) x 2 (FOV) x 5 (interface) completely repeated measures ANOVA. The ANOVA confirmed that air targets were designated significantly more rapidly than ground targets, $F(1,11) = 969.25$, $p < .05$, $\omega^2 = .73$. In addition, the analysis revealed that designation times were significantly faster for targets initially *outside* the FOV (M = 4301msec) than for those initially inside the FOV (M = 4484msec), $F(1,11) = 12.44$, $p < .05$, $\omega^2 = .01$, and that designation times differed significantly among the interface conditions. Designation times in the Visual [Vis] cueing condition tended to be greater than those in all of the conditions featuring audio-visual cueing (M_{Vis}, = 4597msec, $M_{Adap(V)+A}$, = 4490msec, M_{A+V}, = 4314msec, $M_{Adap(A)+V}$, = 4293msec , $M_{Adap(A+V)}$, = 4269msec); $F(2, 20) = 5.21$, $p < .05$, $\omega^2 = .02$. In addition to the main effects, all of the two-way interactions in the analysis were statistically significant: Target x FOV, $F(1,11) = 6.80$, $p < .05$, $\omega^2 = .02$; Target x Interface $F(2, 20) = 7.36$, $p < .05$, $\omega^2 = .73$; FOV x Interface, $F(2, 20) = 4.36$, $p < .05$, $\omega^2 = .01$, as was the higher-order interaction between target, FOV, and interface, $F(2,20) = 6.85$, $p < .05$, $\omega^2 = .01$.

The nature of the three-way interaction can be seen in Figure 10. The longer time needed for target designation in the Visual as compared to all of the audio-visual cueing conditions, approximately 825msec, is apparent for ground targets appearing outside the field of view. The consistent disadvantage for the Visual cueing condition is not apparent for ground targets inside the field of view nor for air targets whether inside or outside the field of view.

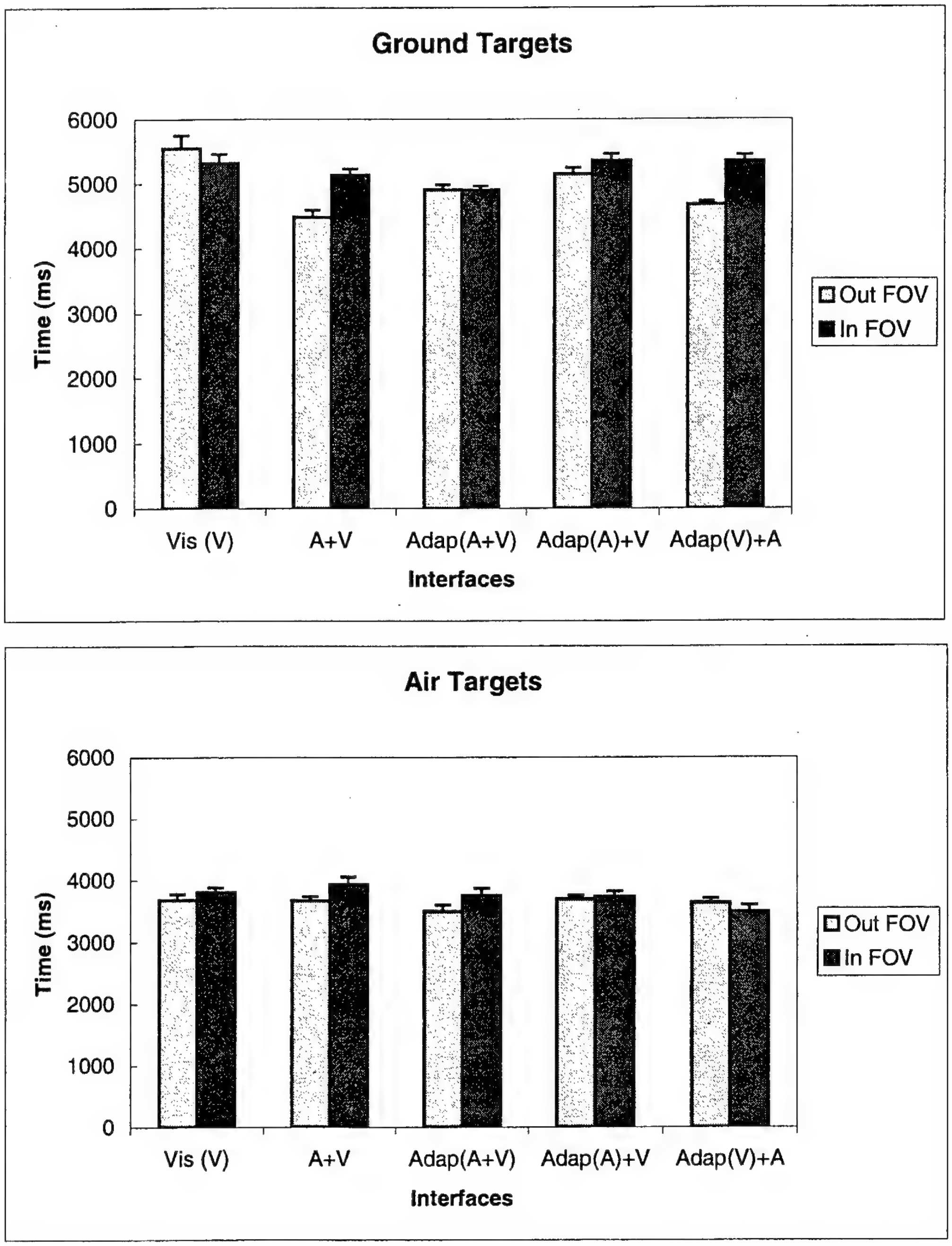


Figure 10. Mean times to designate ground (upper panel) and air (lower panel) targets for five of the interface conditions. Data are provided for targets initially outside and inside the central field-of-view (FOV). Error bars are standard errors.

Head Motion

An analysis of head motion over time was carried out within each interface condition. Figures 11a through 11g portray the track of head motion in *azimuth* (angular deviation in the horizontal plane from the aircraft boresight) and *elevation* (angular deviation in the vertical plane from the aircraft boresight) for several subjects during a representative trial for each of the interface conditions. It can be seen in Figure 11a that the Non-Cueing condition resulted in repetitive head motions (indicated by the density of the track) that ranged widely in azimuth (signified by the spread of the track), suggesting that pilots were making active and continuous visual sweep searches. In the Auditory cueing condition, Figure 11b, there is a drop in the density and range of head motion. Figures for the subsequent interface conditions, 11c-11g, reveal dramatic declines in the repetitiveness (density of the track) and lateral deviation of the pilots' head movements, declines which appear greater than in the auditory alone condition.

Head position data were used to calculate a single metric of head motion, *angular head displacement* - the total angular distance the head traveled throughout an experimental trial[4]. The mean angular head displacement over trials is provided for each interface condition in Figure 12. The data for one participant were dropped for the purposes of this analysis, as a preliminary review of the data indicated that this participant's head motion was excessive (> 2 S.D. above the group mean).

The data of Figure 12 were subjected to a repeated measures ANOVA, which revealed a significant difference among the interface conditions, $\underline{F}(2,20) = 187.03$, $\underline{p} < .05$, $\omega^2 = .75$. Supplementary Newman-Keuls tests (alpha = .05 for each comparison) indicated that the degree of angular head displacement was significantly greater in the Non-Cueing [Non] and Auditory [Aud] conditions than in any of the other conditions and that the Non-Cueing condition was associated with greater angular head displacement than the Auditory condition. None of the comparisons among the remaining cueing conditions was significant.

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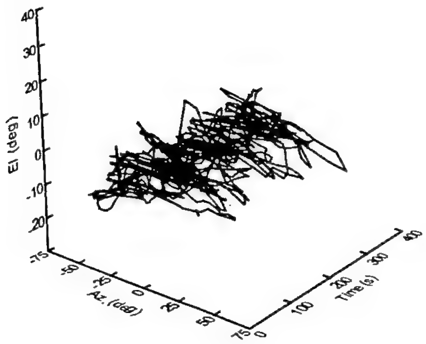
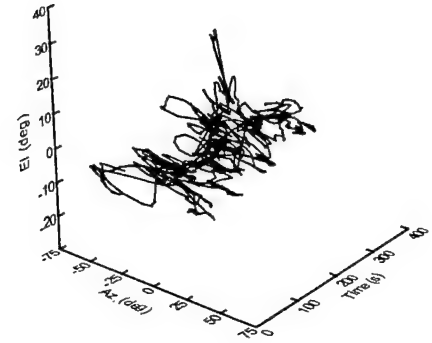
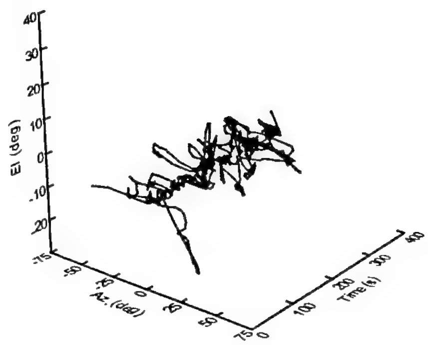
[4] Angular distance was determined by the sum of the differences between consecutive head positions over a trial, which were computed by the formula: tan-1[((xi – xl-1)2 + (yi – yl-1)2 + (Zi – Zl-1)2)]1/2. Where (x,y,z) is a point on a sphere, given that "i" refers to the initial position and "l" to the last position for any consecutive pair of head positions (Cunningham, Nelson, Hettinger, Haas, & Russell, 1996).



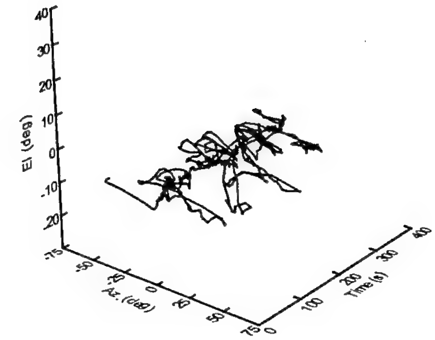
11a. Non



11b. Aud (A)

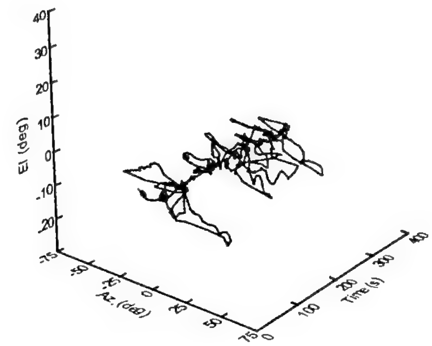


11c. Vis (V)

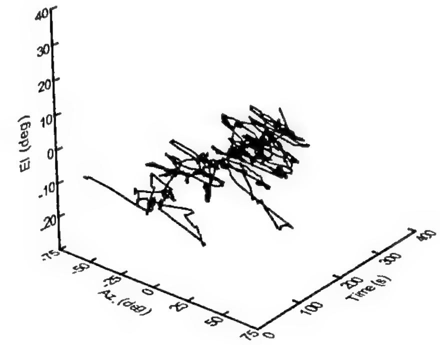


11d. A+V

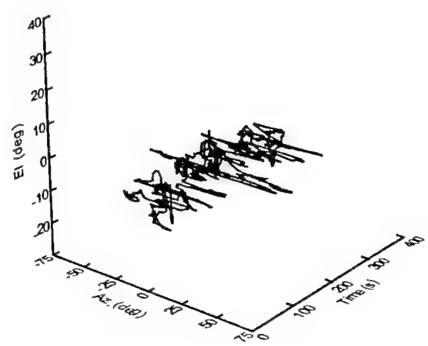
Figures 11a-11g. Head motion plots in azimuth (Az.) and elevation (El.) for a representative trial in each of the seven interface conditions. Axes are scaled to the dimensions of the out-the-window scene (150^0 horizontal x 70^0 vertical).



11e. Adap(A+V)



11f. Adap(A)+V



11g. Adap(V)+A

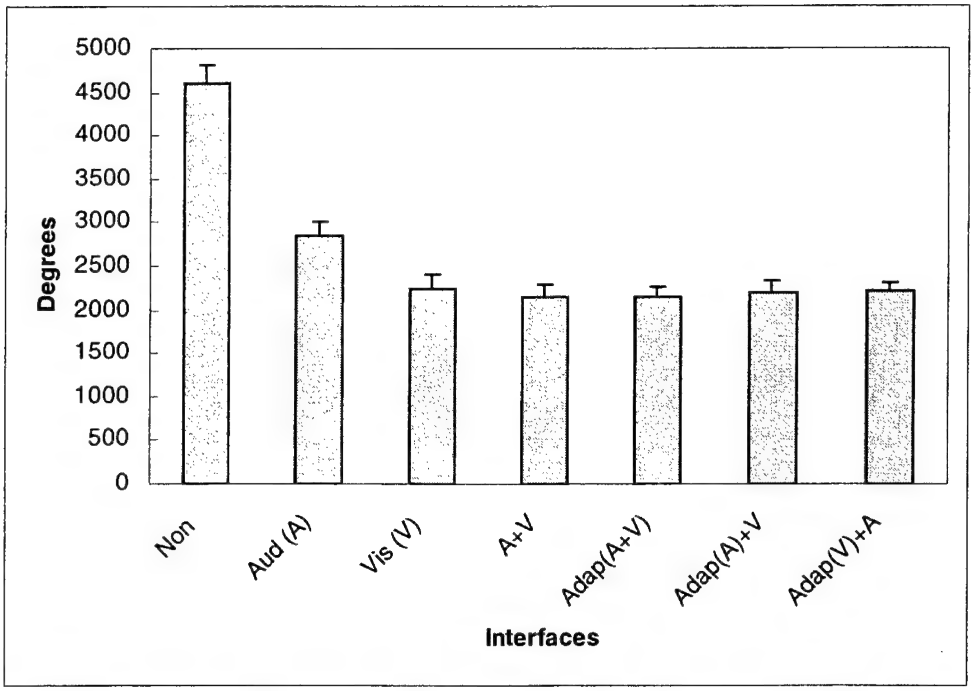


Figure 12. Mean angular head displacement for the seven interface conditions. Error bars are standard errors.

Flight Performance

Deviations from prescribed airspeed, flight path, and altitude (AGL) were used to determine the degree to which the different interface conditions affected flight performance.

Airspeed Error. Root-mean-square (RMS) airspeed error (above or below 500 knots or nautical mph) averaged over trials is presented for each interface condition in Figure 13. A repeated measures ANOVA of the airspeed error data revealed no significant differences among the interface conditions $\underline{F}(2,20) = 3.00$, $\underline{p} > .05$.

Lateral Error. Lateral error was measured as the RMS of horizontal deviations in feet from the flight path averaged over trials. Mean lateral RMS errors for the seven interface conditions are presented in Figure 14. It is evident in the figure that the Auditory [Aud] condition was associated with the greatest amount of error. A repeated measures ANOVA of the lateral error data together with supplementary Newman-Keuls tests (alpha = .05 for each comparison) confirmed that there were significant differences among the interfaces, $\underline{F}(3,30) = 4.32$, $\underline{p} < .05$, ω^2

= .17, and that the Auditory interface led to a greater amount of lateral error than each of the other conditions except the Non-Cueing condition. No other comparison among the interface conditions was statistically significant.

Above-Ground-Level Error. AGL (above-ground-level) error was measured in terms of the RMS of deviations above 300 feet AGL averaged over trials. Mean AGL errors for the several interface conditions are displayed in Figure 15. A repeated measures analysis of variance of the AGL error data revealed that there were significant differences among the interfaces $\underline{F}(4,40) = 3.11$, $\underline{p} < .05$, $\omega^2 = .09$. Supplementary Newman-Keuls tests (alpha = .05 for each comparison), used to further specify the nature of these differences indicated that the Visual [Vis] interface condition was associated with a significantly smaller degree of AGL error than any of the other conditions except the Non-Cueing [Non] and the Adaptive Auditory plus Adaptive Visual [Adap(A+V)] conditions. All other comparisons among the interface conditions were not statistically significant ($\underline{p} > .05$).

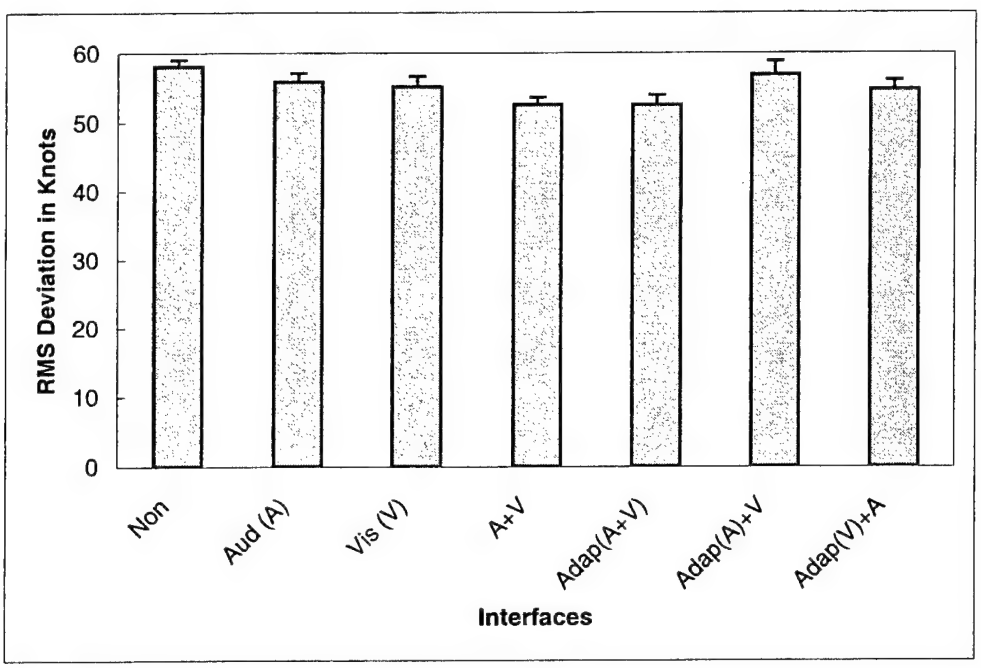


Figure 13. Mean RMS deviations from prescribed airspeed (500 knots) in knots for the seven interface conditions. Error bars are standard errors.

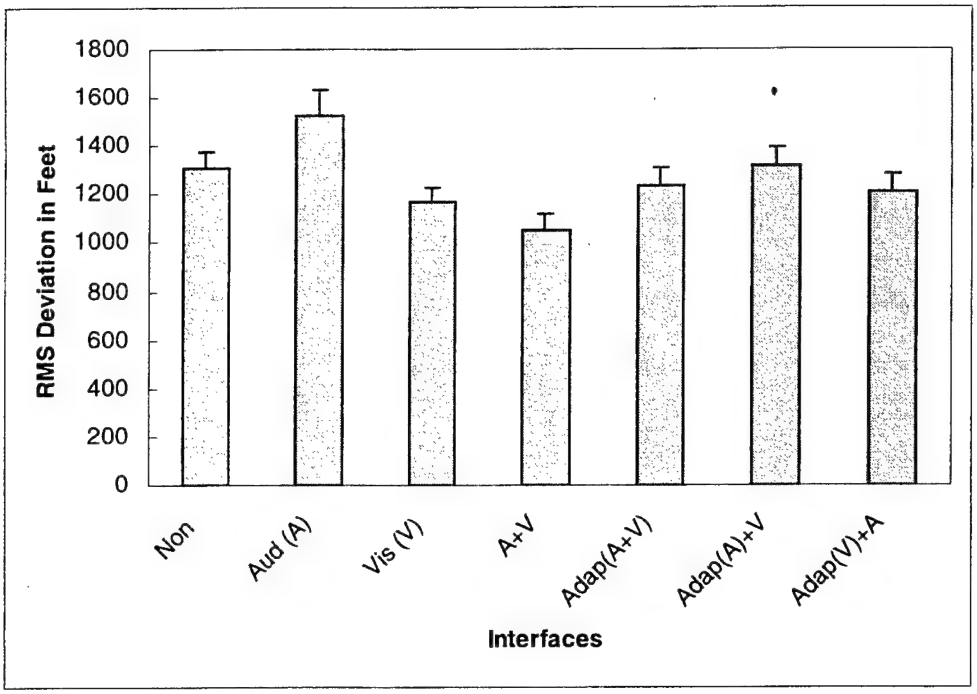


Figure 14. Mean RMS lateral deviations from flight path in feet for the seven interface conditions. Error bars are standard errors.

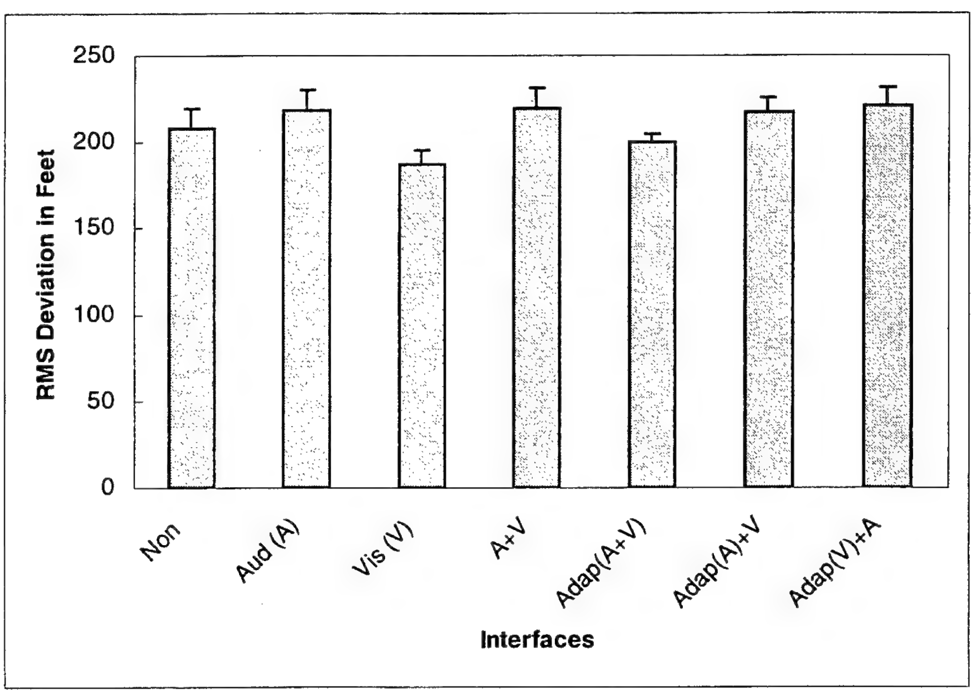


Figure 15. Mean RMS deviations in feet above the prescribed AGL altitude for the seven interface conditions. Error bars are standard errors.

Subjective Workload

Mean global workload ratings on the NASA-TLX are presented for the seven interface conditions in Figure 16. It can be seen in the figure that ratings for the Non-Cueing [Non] and Auditory [Aud] conditions fell within the upper half of the workload scale, and were approximately 50% greater than those for the remaining interfaces which fell within the lower half of the scale. A repeated measures ANOVA confirmed that there were statistically significant differences in the workload associated with the several interfaces, $\underline{F}(3,30) = 12.80$, $\underline{p} < .05$, $\omega^2 = .30$. Supplementary Newman-Keuls tests (alpha = .05 for each comparison) indicated that the overall workload associated with both the Non-Cueing and Auditory interfaces was greater than that for each of the other interfaces. The workload ratings for both the Non-Cueing and Auditory conditions did not differ significantly from each other, and none of the remaining comparisons among the interface conditions reached significance ($\underline{p} > .05$).

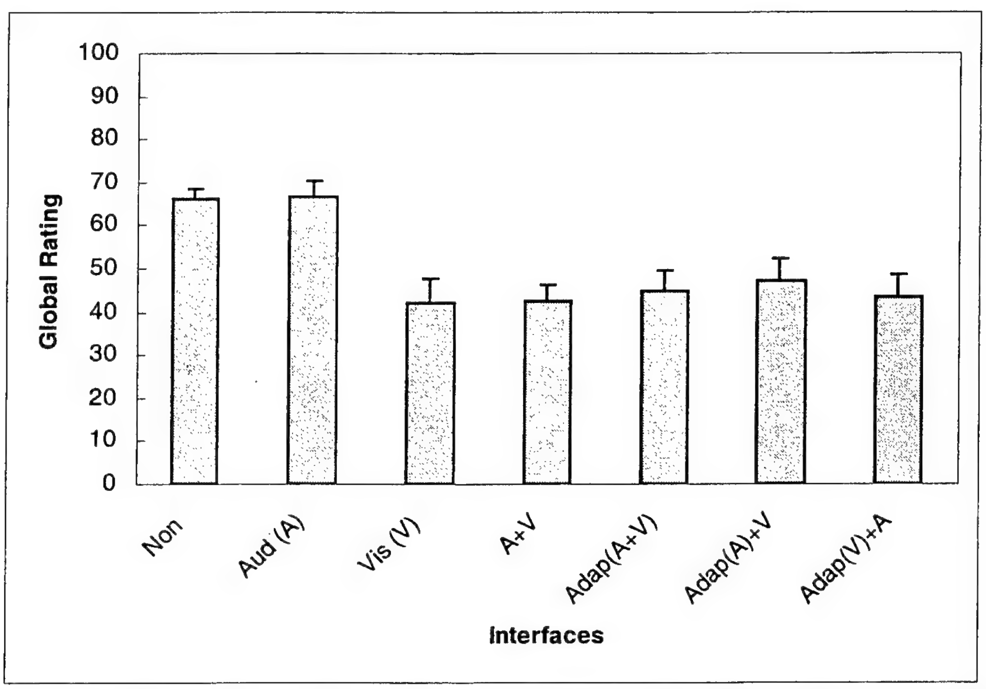


Figure 16. Mean global workload ratings for the seven interface conditions. Error bars are standard errors.

CHAPTER 4

Discussion

In order to meet the demands of tactical missions, it is necessary for pilots to rapidly acquire and act on information from sources both within (near-domain) and beyond (far-domain) the cockpit. Conformal displays such as HUDs and see-through HMDs were designed to reduce the demands and errors associated with switching line-of-sight between domains. Although these displays enhance visual search performance for both ground and air targets (Arbak, King, Jauer, and Adam, 1988; Fadden, Ververs, & Wickens, 1998; Martin-Emerson & Wickens, 1997; Olson, Arbak, and Jauer, 1991; Osgood, Wells, and Meador, 1995; Weintraub & Ensing, 1992), their utility is constrained by their limited field-of-view. The purpose of the present study was to determine the efficacy of supplementing a simulated HMD with spatialized auditory cues presented in unimodal, mutlimodal, or adaptive formats during a flight-based target search task. Audio-visual cueing has been shown to bolster the likelihood of target detection in visual search tasks and to reduce search time and workload (Bronkhorst, Veltman, & Breda, 1996; Nelson, Hettinger, Cunningham, Brickman, Haas, & McKinley, 1998). However, these findings are based upon studies that did not provide supplementary visual cueing via see-through HMDs, the type of HMD most often used in tactical aviation.

Visual Search Performance

Target Designation Accuracy. In order to destroy targets, pilots must locate and designate them correctly. Thus, in this investigation the percentage of targets correctly designated was of principal concern. The major finding with this measure was that the Non-Cueing and unimodal Auditory cueing conditions resulted in considerably lower hit rates for ground and air targets than any of the other cueing conditions (Visual [Vis], Auditory plus Visual[A+V], Adaptive Auditory plus Adaptive Visual[Adap(A+V)], Adaptive Auditory plus Visual[Adap(A)+V], Adaptive Visual plus Auditory[Adap(V)+A]), which, in turn, did not differ

among themselves. In addition, performance in the unimodal Auditory condition was superior to that in the Non-Cueing condition, but only for the ground targets, which were more difficult to detect.

The relatively poor performance for the Non-Cueing condition was predicted, since in that condition pilots were not provided assistance in detecting targets. However, the limited ability of spatialized auditory cueing to aid target designation by itself or to enhance the effectiveness of visual cueing was not consistent with expectations, which were based upon the beneficial role found for spatialized auditory cueing in other investigations (Perrott, et al. 1996; Rudmann & Strybel, 1999). This disparity may be attributable, in part, to the resolution capabilities of the Convolvotron system, which relied on generic HRTFs to interpolate source locations that were not among the 72 locations sampled directly by the system. Indeed, an evaluation conducted in the SIRE facility indicated that localization error for the Convolvotron system averaged 6 degrees under optimal conditions (Moroney, 1999), a value that is approximately three times greater than the spatial resolution error of the human auditory system (Perrott, et al. 1990). It is noteworthy that previous research conducted at the SIRE facility used this equipment to enhance performance in search tasks (Nelson, et al. 1998), but unlike the present case, the tasks did not involve simulated flight and the targets to be detected were embedded in a uniform dark field rather then the realistic scene used here (desert terrain and light blue sky).

In addition to the spatial resolution problem, it may be important that the pilots in this study were highly skilled in the use of visual flight instruments including, HUDs and HMDs. Their familiarity with visual displays, coupled with their relatively limited exposure and training with the auditory cueing system, suggest that pilots may have relied mostly on the visual display and the search behaviors associated with that display. Consistent with this, several pilots, on debriefing, reported that they utilized auditory cueing to alert them to the presence of a target and to the general region in which to perform a visual search, but not for precise spatial localization.

Given the results obtained with the designation accuracy measure, one might conclude that the presence of a visual cue was the necessary and sufficient factor to bolster performance efficiency in this study. It is worth noting, however, that designation accuracy is a gross measure

of visual search performance. Accordingly, it may not reflect subtle contributions to target search made by the integration of audio and visual displays which might appear in a more fine-grained speed measure. Such contributions, if observable, could be potentially quite important, since the time to locate and select a target is a critical factor in air combat. The first shot advantage greatly increases the probability of a kill, and reduces the exposure to potential threats (Barnes, 1989; Shaw, 1988). Consequently, time to designate targets in the Visual and multimodal cueing conditions was also examined.

Designation Time. Results with regard to designation time revealed a benefit for audio-visual cueing relative to visual cueing alone. This benefit was complex, however, involving interactions among target type (ground or air), location in the field of view (FOV) of the display, and cueing condition. For ground targets initially outside of the display FOV, designation time was approximately 825msec slower in the unimodal visual condition than in the fixed and adaptive multimodal cueing conditions. This effect is consistent with the finding of reduced detection time for targets outside the FOV previously reported with the use of spatialized audio cues in visual tasks (Perrott, et al. 1990; Perrott, et al. 1991). The benefit of audio-visual cueing was not observed for ground targets initially inside the display FOV nor was it observable for air targets either inside or outside the display FOV. As was seen in the designation accuracy data, ground targets outside the FOV were the most difficult to detect. Consequently, it appears that the benefit of combining spatialized auditory cueing with visual cueing existed only for targets that were the least salient and, therefore, where supplementary cueing was most needed.

The time differences in designating air versus ground targets, and targets inside the FOV as compared to those outside the FOV, also warrant comment. The significant time advantage noted in this study (> 1000msec) for air over ground targets may be due to the relatively low-contrast between the ground targets and the terrain, which made it difficult to separate target from background as evidenced by the lower hit rates for the ground as compared to the air targets. The finding that adding spatialized auditory cues to a visual localization interface enhanced the speed of ground target designation supports recent research demonstrating the utility of auditory

cueing in visually demanding search tasks (Bolia, D'Angelo, & McKinley, in press; Rudmann & Strybel, 1999).

The designation time advantage for targets initially outside of the FOV over those within the central FOV was unexpected given the higher hit rates for the latter than the former. One possible explanation for this result is that targets initially within the central FOV were usually in the flight path, possibly affording pilots more time to designate them while handling other flight demands. In contrast, targets outside the central FOV were more likely to be off the flight-path axis, which meant that they were likely to disappear quickly from the OTW view (off the screen) and needed to be responded to immediately or be lost. It is unlikely, however, that pilots intentionally delayed designating targets given their knowledge that speed counts in combat.

An alternative explanation is that attention to the HUD and HMD may have reduced sensitivity to targets initially in the central FOV. Several researchers (Boston & Braun, 1996; Dudfield, Hardiman, & Selcon, 1995; Long & Wickens, 1994; Martin-Emerson & Wickens, 1997; McCann & Foyle, 1994; Ververs & Wickens, 1996; Weintraub & Ensing, 1992) have addressed the issue of having to switch visual attention between displayed information and the out-the-window view when using HUDs and HMDs. Although these conformal displays eliminate the need to physically shift one's head or gaze between locations, it is still necessary to shift attention between the display and the outside scene (Boston & Braun, 1994). Research into this phenomenon has demonstrated that when symbology overlaps the outside visual scene it can obscure the OTW view and pull a pilot's attention away from that scene ("cognitive fixation"). As a result, responses to far-domain events are delayed (Long & Wickens, 1994; Martin-Emerson & Wickens, 1997). Additionally, response delay for events in the far domain is a function of the density of events in the near domain: the greater the number of elements in the near domain, the longer the response time to events in the far domain (Martin-Emerson & Wickens, 1997; Ververs & Wickens, 1996). In the present study, targets that were initially in the central FOV tended to fall within the display areas of both the HUD and the HMD, resulting in a dense visual field. In comparison, targets outside of the FOV appeared in a less dense visual field since they were less likely to be overlapped by the HUD symbology.

Head Motion

Head motion is another important aspect of visual search performance. Excessive head motion can lead to fatigue and reductions in performance efficiency, particularly when using an HMD in high–*g* environments (Davis, 1997). This measure can also serve as a general indicator of the level of scanning performed, and thereby of the proportion of time available to perform other tasks. Accordingly, head motion in this study was examined descriptively by means of the track of motion in azimuth and elevation and quantitatively in terms of mean angular head displacement. Since pilots in the Non-Cueing condition were not alerted to the presence of targets, one might expect this condition to necessitate constant visual scanning for targets, producing frequent head movements. Consistent with such an expectation, a relatively dense track of head motion and a relatively high amount of angular head displacement occurred in the Non-Cueing condition. As was the case in an earlier study by Nelson et al. (1998), head motion, both in terms of track density and angular displacement, was reduced by the presence of a unimodal spatialized auditory cue. However, the reduction of head motion was even greater in the presence of a unimodal visual cue and combining audio-visual cues did not reduce head motion any more than did visual cueing alone. Thus, the pattern of results for head motion paralleled that for detection accuracy, perhaps because of the limited resolution of the auditory cue and pilots' predominant experience with visual displays.

Flight Performance and Workload

One of the risks of interface development in a complex multitask environment is that performance improvement on one task may come at the expense of efficiency on other tasks (Latorella, 1998; Wickens, 1992). Moreover, the means used to enhance performance may induce unacceptable levels of workload (Proctor and Van Zandt, 1994). To assess these possibilities, the influence of the several cueing conditions on concurrent flight performance was examined along with the subjective workload associated with the cueing conditions. None of the interfaces exceeded the Non-Cueing condition in terms of deviations from the prescribed air speed, flight path, and altitude. Thus, the enhanced search performance produced by the

unimodal visual and multimodal conditions did not come at a cost in pilots' ability to handle other flight-related activities. Moreover, the workload associated with the visual and the multimodal cueing conditions fell at a level (a score of approximately 40 on the NASA-TLX) that is considered acceptable in flight simulation tasks (Moroney, 1999) and was significantly lower that that in the Non-Cueing and unimodal Auditory conditions whose means (> 60) fell at a level indicative of a need for reductions in workload in such tasks.

User Feedback

A final consideration is the response of pilots to the various interface configurations, as the pilots are the true end-users and experts. User feedback and acceptance is an extremely important aspect of interface design (Nielsen, 1993; Shneiderman, 1992), since even the best designed interface is of no value if people chose not to use it. In this experiment, pilots responded favorably to the various interfaces, including the adaptive configurations in which they were confronted with the need to switch between auditory and visual information. As indicated above, pilots reported that the auditory cue was useful as an alerting mechanism to the presence of a target. They also suggested that it would be even more valuable if localization resolution could be improved so that head motion would not be needed to precisely determine the position of a target. In addition, the pilots indicated the transition between audio and visual information in the adaptive conditions was easy to accomplish.

Conclusions

The first goal of this research was to determine whether multimodal localization cueing would aid in visual search performance when using a simulated HMD. The expected benefits of auditory cueing in conjunction with visual cueing were not present in regard to the accuracy of target designation. At first glance, a result of this sort would seem to support the findings of Flanagan et al. (1998), who reported that visual search performance with an opaque HMD is not aided by the addition of spatialized auditory cueing. On the other hand, the present study demonstrated that when the speed of target designation is considered, the addition of spatialized

sound to a visual cue does enhance performance efficiency in comparison to the visual cue alone under conditions in which targets are most difficult to detect. This finding is of considerable practical significance since even slight time advantages can be critical in the domain of tactical aviation. In addition, multimodal cueing had the added benefits of reducing excessive head motion and lowering pilots' workload in comparison to a case in which no cueing was available. Moreover, the benefits associated with multimodal cueing did not incur a performance-resource debt (cf. Wickens, 1992), in which performance on concurrent flight tasks was sacrificed for enhancement in the speed of target detection. In sum, the present study suggests that multimodal cues may effectively aid target localization when using a see-through HMD in tactical aviation.

A second goal for this study was to explore the potential advantages of the adaptive presentation of multimodal cueing information. Unlike previous studies by Brickman et al. (1996) and Moroney (1999), the present investigation revealed no advantage for presenting multimodal information adaptively over presenting it in a fixed format; that is, the benefits associated with multimodal information were identical in both formats since the scores for the Auditory plus Visual [A+V] condition were similar to those of the Adaptive Auditory plus Adaptive Visual [Adapt (A+V)], Adaptive Auditory plus Visual [Adapt (A) +V], and Adaptive Visual plus Auditory [Adap (V) + A} conditions with respect to the speed and accuracy of target detection and reductions in head motion and workload. The failure of the adaptive conditions to prevail over the fixed format conditions in this study may stem from the fact that the adaptive format was not necessary in the flight scenario used here. Recall that the purpose of the adaptive format was to reduce cockpit clutter. Since it turned out that the fixed multimodal interface did not interfere with the performance of the concomitant flight tasks, there was no added benefit in clutter reduction to be gained through the adaptive format.

Implications for Future Research

The results of this research suggest several avenues for further study. It would be of value to determine whether the difficulty-specific advantage found for multimodal cueing is also

present in other visually restricted search tasks such as those performed in night-vision and inclement weather conditions, as well as in low-resolution virtual environments.

One feature of the present study that could be improved upon is the presentation of spatialized auditory cues. Clearly, future research should examine the efficacy of auditory cueing with conformal visual displays using a higher resolution auditory system than that used herein. Also, the utility of multimodal localization interfaces might be revealed more effectively when pilots are exposed to such interfaces early in their flight training rather than, as in the present case, testing them after they have had substantial experience in relying solely on visual displays. Extensive training with auditory displays and virtual sound localization tasks may also aid seasoned pilots in using multimodal interfaces

The usefulness of an adaptive format in reducing the demands of cockpit clutter when presenting multimodal information about target localization might emerge in a flight scenario requiring greater attention to displays of near domain information then what was called for in this study. Near-domain load could be increased by adding additional head-down displays and their related tasks. These could include systems management, communication, and mission planning procedures.

The unexpected finding of a time disadvantage in designating targets initially within the display field-of-view might also be addressed by an adaptive interface approach. More specifically, it might be useful to employ an adaptive procedure to remove non-critical conformal display elements when a target is present in the display field of view, or even to temporarily shift some of those elements to an auditory display.

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APPENDIX A

Analysis Summary Tables

Table A1

Analysis of Variance for Target Designation Accuracy.

Source	df	df (adj.)	MS	F	P
Target (A)	1		27.82	463.67	<.05
FOV (B)	1		8.99	99.89	<.05
Interface (C)	6	3	6.78	61.64	<.05
AB	1		0.11	1.57	n.s.
AC	6	3	0.86	17.20	<.05
BC	6	3	0.18	1.80	n.s.
ABC	6	3	0.08	1.14	n.s.
Subjects (S)	11		0.08		
SA	11		0.06		
SB	11		0.09		
SC	66	40	0.11		
SAB	11		0.07		
SAC	66	40	0.05		
SBC	66	40	0.10		
SABC	66	40	0.07		

Table A2

Analysis of Variance for Ground Target Designation Accuracy.

Source	df	df (adj.)	MS	F	p
Interface (A)	6	3	3.10	77.50	<.05
Subjects (S)	11		0.05		
SA	66	40	0.04		

Table A3

Analysis of Variance for Air Target Designation Accuracy.

Source	df	df (adj.)	MS	F	P
Interface (A)	6	3	0.72	18.00	<.05
Subjects (S)	11		0.02		
SA	66	40	0.04		

Table A4

Analysis of Variance for Designation Time.

Source	df	df (adj.)	MS	F	P
Target (A)	1		116.31	969.25	<.05
FOV (B)	1		1.99	12.44	<.05
Interface (C)	4	2	.99	5.21	<.05
AB	1		.34	6.80	<.05
AC	4	2	.81	7.36	<.05
BC	4	2	.436	4.36	<.05
ABC	4	2	.685	6.85	<.05
Subjects (S)	11		.14		
SA	11		.12		
SB	11		.16		
SC	44	20	.19		
SAB	11		.05		
SAC	44	20	.11		
SBC	44	20	.10		
SABC	44	20	.10		

Table A5

Analysis of Variance for Angular Head Displacement.

Source	df	df (adj.)	MS	F	P
Interface (A)	6	2	9041324.27	187.03	<.05
Subjects (S)	10		1510184.49		
SA	60	20	48342.329		

Table A6

Analysis of Variance for RMS Airspeed Error.

Source	df	df (adj.)	MS	F	p
Interface (A)	6	2	51.04	3.00	n.s.
Subjects (S)	11		52.11		
SA	66	20	17.03		

Table A7

Analysis of Variance for RMS Lateral Error.

Source	df	df (adj.)	MS	F	P
Interface (A)	6	3	265006.90	4.32	<.05
Subjects (S)	11		100977.98		
SA	66	30	61400.32		

Table A8

Analysis of Variance for RMS Above-Ground-Level Error.

Source	df	df (adj.)	MS	F	P
Interface (A)	6	4	1921.93	3.11	<.05
Subjects (S)	11		3544.58		
SA	66	40	617.95		

Table A9

Analysis of Variance for Global Workload Ratings.

Source	df	df (adj.)	MS	F	P
Interface (A)	6	3	1483.08	12.80	<.05
Subjects (S)	11		943.31		
SA	66	30	115.83		

APPENDIX B

List of Abbreviations and Acronyms

Interfaces

Non	Non-cueing
Aud	Auditory
Vis	Visual
A+V	Auditory plus Visual
Adap(A+V)	Adaptive Auditory plus Adaptive Visual
Adap(A)+V	Adaptive Auditory plus Visual
Adap(V)+A	Adaptive Visual plus Auditory

Acronyms

AGL	Above-ground-level altitude
FOR	Field-of-regard
FOV	Field-of-view
HMD	Helmet-mounted display
HMS	Helmet-mounted sight
HOBS	High off-axis boresight weapons system
HRTF	Head-related transfer function
HSD	Horizontal situation display
HUD	Head-up display
LOS	Line-of-sight
OTW	Out-the-window
RMS	Root mean square
SIRE	Synthesized Immersion Research Environment